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A review of the geology and geotechnical characteristics of Champlain Sea clays of the Ottawa River Valley with reference to slope failures

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A REVIEW OF THE GEOLOGY AND GEOTECHNICAL CHARACTERISTICS OF CHAMPLAIN SEA CLAYS OF THE OTTAWA RIVER VALLEY WITH REFERENCE TO SLOPE FAILURES

J.S.Scott

Abstract

Late Glacial marine clays, commonly known as Leda clay or Champlain Sea clay, are of widespread occurrence throughout the Ottawa-St. Lawrence lowlands. Slopes of river valleys incised into these deposits are prone to slope failures thereby constituting one of the principal terrain hazards affecting both property and life in eastern Canada.

Champlain Sea clays were deposited in a marine estuarine-type environment marginal to a receding continental glacier ice front. The sediments comprise primarily clay-sized particles ($\leq 2\mu$) of generally non-clay minerals that were rapidly deposited in an ephemeral basin of deposition which persisted for the period approximately 12,000 - 10,000 yrs. B.P. During this period the basin was uplifted about 135m through crustal rebound. As a result of the rapid rate of sedimentation and their textural/mineralogical character the sediments are underconsolidated with respect to the void ratio - effective stress relations that exist in the field.

Fundamental to understanding the geotechnical behaviour of geological materials is an evaluation of readily measured properties of both the soil grains and soil aggregates (index properties) and the variation in these properties with depth. For Champlain Sea clays field moisture content and Liquidity Index are particularly important index properties as indicators of the potential for regressive flow sliding in these materials. Soil profiles for Champlain Sea clays at a number of locations east of Ottawa show, for soils below the near-surface desiccated layer, that moisture contents are close to or above the liquid limit and that values of the Liquidity Index are commonly >1. A review of selected references from the geotechnical literature has shown that water content of Champlain Sea clays and similar sediments has a significant influence upon the values of undisturbed and remolded shear strength, sensitivity, liquidity index, effective stress and permeability.

As a consequence of the relationship between water content and the several geotechnical parameters noted above field sampling to determine moisture content and Atterberg limits values with depth can be effectively used in concert with other slope attributes to assess the potential for various types of slope failures in Champlain Sea clays.

Introduction

The Late Glacial marine clays, commonly known as Leda clay or Champlain Sea clay, are of widespread occurrence throughout the Ottawa and St. Lawrence River valleys. These clays are well known as being susceptible to landslides. Most of these landslides occur along the numerous valley slopes of rivers that have eroded into these deposits since the retreat of continental glaciers from the region approximately 10,000 years ago. As noted by Evans (1997) the potential for landslides in the Champlain Sea clays constitutes one of the principal terrain hazards affecting both property and life in eastern Canada.

As a natural terrain hazard and problematic material for foundations or excavations it is understandable that Champlain Sea clays have received considerable attention from both geologists and soils engineers over the past several decades. An indication of the extent to which Champlain Sea clays have been the subject of geotechnical research or evaluation during the period 1965 -1996 is given by my analysis (Fig. 1) of articles published in the Canadian Geotechnical Journal. It may be seen from this analysis that geotechnical interest in Champlain Sea clays appears to have declined since about 1980. The publication record for the above noted period, however, also indicates a substantial accumulation of information about the character and behaviour of these clays.

In June of 1993 a flowslide involving between 2.5 and 3.5 million cubic meters of material occurred on the right bank of the South Nation River near the site of the former village of Lemieux located approximately 50 kilometers east of Ottawa and 10 kilometers northeast of the town of Casselman, Ontario (Fig. 2) This occurrence, described in detail by Brooks et al. (1993), fortunately involved no loss of life but did cause injury to one individual who was unable to prevent his vehicle from entering the rapidly developing crater which destroyed the road before him. This landslide was but one of many landslides to occur along the river during historic and more recent times. The event served to focus the attention of land use planners and municipal officials on the need for methods to evaluate the magnitude and extent of landslide hazard on land adjacent to the river.

At the time of the Lemieux landslide I had recently retired from the Geological Survey of Canada and had been appointed by the Survey as a scientist emeritus. It had been my intention to undertake a review project pertaining to landslides. The occurrence of the Lemieux slide thus prompted me to examine the literature pertaining to the geology and geotechnique of Champlain Sea clays, particularly within the Ottawa River valley, with the aim of increasing my understanding of a.) the role of the geological history of the deposits in contributing to their geotechnical characteristics and b.) possibly identifying one or more geotechnical parameters that would be of particular use to the regional geological evaluation of the landslide hazard posed by Champlain Sea clays.

In order to understand the geotechnical behaviour of a soil or a soil sequence one must understand a number of factors or attributes of the soil or soil sequence that derive from their geological history. These factors or attributes include the source, texture and mineralogy of the sediment, depositional history and environment, consolidation history and any post-depositional forces or changes to which the sediments may have been subject. The events and processes that effect the geotechnical properties of clay sediments in a depositional basin have been referred to by

Chandler, (2000) as the "Geotechnical Cycle" but with recognition that the elements of the cycle are essentially geological or geomorphological in nature. For sediments deposited in periglacial environments such as Champlain Sea clays, however, consideration must also be given to the probable hydrogeological regime that existed within the receding ice-front and the extent to which this regime may have influenced pore pressures, and hence the rate of consolidation of sediments, within the basin of deposition.

Given that this review was supported by the Geological Survey and was intended primarily for a geological audience, I felt it appropriate to include herein a rather extensive introduction to the description of soil index properties and to the concepts of soil consolidation as these aspects of soil mechanics may not be familiar to many geologists.

Characteristics and Properties of Soils

Fundamental to the understanding of the geotechnical behaviour of geological materials is an evaluation of the readily measured properties of both the soil grains and soil aggregates. Included among these index properties for soil grains are size and shape of the grains (texture) which correlate with soil behaviour. For the soil aggregates, index properties include relationships among the weights and volumes of the solids, liquids and gasses that are soil constituents. Variations in the values for the relationships of these soil constituents with depth can be strongly indicative of soil behaviour.

Weight/volume relationships

The total volume of a unit of soil (V) comprises the sum of the volume of solids (Vs), volume of water (Vw), and the volume of gas (Vg). The sum of Vw +Vg is equal to the volume of the voids (Vv). Similarly, the total weight of an element of soil (W) is equal to the sum of the weight of the solids (Ws) plus the weight of the voids (Ww). These weight/volume relationships described by Peck et al.(1953) are shown diagrammatically in Fig.3. From these basic relationships several other useful soil aggregate parameters can be derived. Among these are: Porosity (n), where n = Vv/V for which both numerator and denominator change upon compression of the soil and the Void Ratio (e), where e = Vv/Vs in which reductions in void space due to compression are related to an unchanging denominator.

Water Content and Void Ratio

Water content (w%), is one of the most important soil index properties. It is defined as Ww/Ws x 100 where Ww equals the weight of the soil moisture and Ws equals the weight of the soil solids following oven drying of the soil at a temperature between 100° and 110° C. Thus, the weight of water is referred to the unchanging weight of solids rather than to the variable total weight of the soil. The extent or degree of saturation of a soil is defined as Sr = Vw/Vv x 100. Soils below the water table may contain both gas (air) and water and are commonly fully saturated whereas soils above the water table usually contain both gas (air) and water and are generally less than fully saturated.

Since the water in soils, apart from that contained in hydrous minerals or bonded to soil particles, is contained within the void spaces, a relationship exists between void ratio and water content. For fully saturated soils the relationship as given by Lambe (1951) is:

$$e = Gs.w$$

where e is the void ratio, Gs is the specific gravity of the soil solids and w is the water content. For many soils the value of the specific gravity of the soil solids is in the range of 2.70 - 2.75 thus, if the water content of a soil is known and total saturation can be reasonably assumed, a close approximation of the void ratio can be readily obtained.

Soil consistency (Atterberg Limits)

The geotechnical behaviour and properties of clayey soils are dependent upon the consistency of the soil which is governed by the soil's moisture content. Early in the 20th century a noted European soil scientist named Atterberg quantified through measurement of water contents the consistency states of clayey soils as they changed from liquid to plastic to solid states with progressive reduction in moisture content. Atterberg's use of water contents to express the transition points between states of soil consistency was adopted in the early stages in the development of soil mechanics and remains as the well known Atterberg Limits of liquid limit and plastic limit. By definition the liquid limit (w_l) is the water content at which a soil passes from a plastic state to a liquid state and the plastic limit (w_p) is the water content at which the soil passes from a plastic to a solid state. The numerical difference between the two limit states is known as the Plasticity Index (I_p). For many soils the natural or field moisture content (w_n) is commonly somewhere between the liquid and plastic limits but, as will be seen, some soils exist in a seemingly solid state with water contents at or well above the liquid limit.

Liquidity Index

A particularly useful parameter for expressing the consistency state of a soil is the Liquidty Index (I_l) which is determined by the relationship $w_n - w_p / w_l - w_p$ or $w_n - w_p / I_{p.}$ It is apparent from this relationship the value of $I_l = 1$ for soils with moisture content at the liquid limit; >1 for soils with moisture contents above the liquid limit; and <1 for soils with moisture contents below the liquid limit. It is further apparent that soils having moisture contents above the liquid limit will be transformed from a solid or plastic substance to a fluid upon remolding.

Consolidation States of Clayey Soils

Basins of deposition in which clayey sediments accumulate occur in a wide variety of geological and geomorphological settings, areal dimensions and duration over time. Water conditions within the basin including depth, salinity, temperature, current velocities and directions can also be highly variable over the life of the basin. In addition, the geological provenance of sediments along with the type and extent of weathering, erosion and transport mechanisms will influence the texture, mineralogy and structure of sediments contributed to the basin. Thus, upon uplift to a subaerial environment following deposition each unit of sediment will reflect in its geotechnical behaviour the legacy of its geological history.

As clayey sediments accumulate upon the floor of a basin of deposition their water content at the sediment/water interface is commonly at or somewhat above the liquid limit (Terzaghi, 1941, Skempton, 1944). More recent work by Skempton, (1970) and as reported by Chandler, (2000) reveals that water contents of newly deposited sediments, particularly in marine environments, may be up to 1.8 times its liquid limit. With continuing accumulation of sediment in a basin the older sediments at depth will tend to consolidate under the load or stress imposed by the superjacent sediment. Consolidation of the sediment is accompanied by a decrease in the void ratio and expulsion of pore water from the element of sediment undergoing consolidation. In the initial stage of consolidation the load imposed upon the element of sediment will be carried by the pore water resulting in an increase in pore water pressure. With time, however, the load will be transferred to the sediment particles with attendant decrease in pore water pressure.

The progress of consolidation of an undisturbed soil, whether in the field or in the laboratory, can be illustrated diagrammatically as shown in Figure 4 in which void ratio (e) on an arithmetic scale is plotted against the log of the applied effective pressure (i.e. the total applied pressure minus the pore water pressure). The applied effective pressure may result from incrementally applied loads in a laboratory consolidation test, the submerged weight of accumulating sediment in a basin of deposition, or a load imposed upon a column of soil by some form of construction activity. The rate at which consolidation takes place will be dependent upon such factors as the magnitude of the load increment, permeability of the soil and the length of the drainage path. For laboratory consolidation tests the rate of loading is relatively rapid, drainage paths are very short and, while permeabilities of test specimens may be quite low, the consolidation process is essentially instantaneous. As pointed out by Crawford (1965) the laboratory rate of compression, for a short period after loading, may be several million times faster than that experienced in the field. Thus, the distinction between laboratory and field consolidation is primarily a matter of the rate of loading. In the laboratory loading is relatively rapid by application of load increments at successive but generally short time intervals. In the field the magnitude of load increments is generally very small with either intermittent or continuous application over long periods of time.

Normally consolidated soils

Under conditions where an undisturbed soil consolidates under incremental loading by sediment or by the application of load increments in the laboratory, its consolidation history can be represented by the curve in Fig.4a. Point (a) represents the initial void ratio and load condition, point (b) an intermediate load and void ratio and point (c) a further load and void ratio condition due to sedmentation or laboratory loading. The curve (a) - (b) - (c) and beyond thus portrays a "normally consolidated" soil i.e. one that has not been subject to loading greater than that represented by the load corresponding to any given point on the curve.

Overconsolidated soils

In the event the soil is uplifted and a portion of the soil column is eroded a portion of the previous confining load will have been removed and some measure of rebound, as manifest by an increase in void ratio, will occur. This event is illustrated by the curve in Fig. 4b in which the soil previously loaded to a pressure corresponding to point (c) now exists under a reduced effective pressure corresponding to point (b'). Due to incomplete elasticity of the soil, however, it retains a void ratio less than the magnitude of the void ratio produced by the initial load corresponding to point (b) . Since any element of the uplifted soil now exists under a confining pressure less than the pressure that originally consolidated it, the soil is considered to be "overconsolidated". If subject to reloading by addition of fill, other construction activity or by consolidation testing in the laboratory "overconsolidated" soils will not undergo further consolidation until the imposed load exceeds the preconsolidation pressure corresponding to points (b) and (b') in Fig. 4b.

It may be noted that curves for both "normally consolidated" and "overconsolidated" soils consist of an initial curved portion and a straight line portion as applied effective stress increases. If the void ratio vs. log pressure curves for either consolidation state are converted to a water content vs. depth profile it will be seen that the water content decreases in a systematic manner with depth and, in fact, many soils display such a relationship.

Underconsolidated soils

Not all soils, however, have water content vs. depth profiles that decrease in a systematic manner as noted above. Although they may be considered "normally" consolidated with respect to their loading history, some soils deposited under conditions such as rapid rates of sedimentation and flocculation in saline waters and comprising large volumes of clay-sized particles, but not necessarily clay minerals, tend to be resistant to consolidation. These soils, while apparently existing in a solid state, possess water contents at or above their liquid limits even at considerable depths.

Early recognition of the variation in the relation between depth and void ratio of submerged deposits of normally consolidated uniform clays and the hypothetical compression curve derived from a laboratory compression test was noted by Terzaghi, (1941). He described the water content vs. depth relationships for submerged marine, lacustrine and fluvial clays from respectively, Turkey, Italy and Sweden. In each location at depths of 18m, and in some locations at even greater depths, water contents of the samples collected were at or close to the liquid limits for the clays with no tendency for the water content to decrease with depth. Terzaghi (op.cit.) described the real relation between the void ratio and the very slowly increasing pressure due to the weight of the overburden in a clay deposit during the process of sedimentation as the "sedimentation compression" curve as distinct from the virgin compression curve for the same soil derived from a laboratory compression test.

While initially perplexed by the substantial differences between laboratory compression curves and sedimentation compression curves for the soils that he had encountered in the field Terzaghi (op.cit.) provided an explanation for the differences through the behaviour of solid, adsorbed and liquid water films that surround soil particles and the rate at which the clays are loaded. He called the gradual development of a solid bond between clay particles as the “process of solidification”. Prior to complete solidification of a clay some particles are mutually connected by a solid bond due to direct contact between the solid parts of the adsorbed layers. Other particles are held together by the highly viscous yet liquid portion of the adsorbed layers. Thus, the effective stress applied to the soil comprises two parts viz. solid bond stress and film bond stress. Both types of bond participate in the transmission of pressure from grain to grain. Ultimately, the entire stresses in a clay will be carried by the solid bond and the clay will be in a solid state. Prior to attaining a solid state, however, the film bond stresses which produce a slow, viscous intergranular movement, or lubrication of soil particles, must be decreased. The rate at which such a degree of lubrication diminishes depends upon the quantity of highly viscous adsorbed water requiring displacement and the magnitude of the pressure applied per unit area of the adsorbed water film.

Soils such as those described above may have consolidation curves as portrayed by the curve in Fig. 4c. For a given level of applied stress a soil resistant to consolidation will have a void ratio, and hence, water content substantially higher than that of a "normally" consolidated soil and may thus be considered to be "underconsolidated".

The concept of "underconsolidation" derives primarily from the study of the state of consolidation of soils in the submerged condition as reported by Terzaghi (1941) or in the process of sedimentation. In a study of Mississippi delta sediments in both active and less active (older) sedimentary environments McClelland (1967) defined "underconsolidated" sediments as those having values of the existing Liquidity Index (I_L) greater than the Liquidity Index (I_{Ln}) that would be obtained if the soil were normally consolidated. Values of (I_{Ln}) were obtained from a graphical representation of the relationships among the effective pressure, void ratio and liquid limits for the sediments under study. In general, the water contents for the Mississippi sediments studied by McClelland were all less than the Liquid Limit.

Sangrey et al. (1979) in a study of the geotechnical characteristics of recent marine sediments in Alaskan coastal waters recognized that underconsolidation in marine sediments, particularly fine-grained silts and clays, can result from high rates of sedimentation. They noted that normally consolidated soils are defined as having an in situ state of effective stress equal to the maximum effective stress in the history of the soil. This definition implies that there are no excess pore pressures above hydrostatic and that the vertical effective stress (σ_v') at a given depth for a submerged soil profile would be the product of the unit weight of the submerged soil (γ') and the height (H) of the soil column or $\sigma_v' = \gamma' H$. If the soil is underconsolidated the effective stress is less than $\gamma' H$. by the magnitude of the excess pore pressure.

This definition of "underconsolidation" involving excess pore pressures may well apply to submerged soils in basins of active deposition or otherwise of very recent origin. In the case of young sediments presently existing under subaerial conditions, however, such as the Champlain Sea sediments, excess pore pressures do not exist naturally within the soil column except locally at the base of some slopes. The concept of "underconsolidation" with respect to Champlain Sea deposits is that for a given level of applied effective stress under natural conditions the void ratio of the soil is greater than would be the case for the same level of effective stress applied under consolidation testing in the laboratory. In both the field and laboratory excess pore pressures have dissipated but in the field the soil skeleton is more resistant to void ratio reduction than it is in the laboratory. Soils such as these may also have consolidation curves as portrayed by the curve in Figure 4c. The soil represented in Fig. 4c could also be considered to be in a state of delayed consolidation. If subject to a load represented by point (c) or greater, further consolidation, i.e. reduction in void ratio, could occur. If no further load is imposed the soil may also undergo time dependent consolidation.

Crawford (1965) performed a series of compression tests on undisturbed samples of Champlain Sea clay from the Ottawa area. The tests were carried out at constant rates of compression varying from 0.16 to 8 per cent per hour accompanied by measurement of pore pressures. Results of these stress-compression tests were compared with an average curve obtained by incremental loading. From this comparison Crawford concluded that the compressibility of the soil is dependent upon the average rate of compression and that the soil structure has a substantial time-dependent resistance to compression.

It is also possible that such soils having void ratios, hence water contents, substantially higher than normally consolidated soils at the same level of effective stress may be in a state of delayed consolidation as discussed below.

Delayed consolidation of soils

The concept of time-dependent or delayed consolidation was further developed by Bjerrum (1967) following his review of various geological processes which can take place with time in Norwegian normally-consolidated marine clays. These clays underlie the city of Drammen, Norway and are of postglacial deposition in a marine environment similar to that of the Champlain Sea clays of the Ottawa-St. Lawrence lowlands.

Bjerrum (op. cit.) observed that the compressibility characteristics of a clay showing delayed consolidation cannot be described by a single curve on a void ratio vs. log pressure diagram. Instead, a system of parallel lines or curves separated on a logarithmic time scale is required as shown in Fig. 4d. Each of the lines or curves in Fig. 4d represents an equilibrium void ratio for different values of effective overburden pressure at a specific time of sustained loading.

It may be noted that although consolidation of some soils may be delayed (i.e. time dependent) the consolidation process still produces a reduction in void ratio and a consequent increase in shear strength. The implications of this relationship for settlement calculations and evaluation of consolidation test data are given by Bjerrum(1967).

With respect to the volume change that occurs in the sediment this is divided into two components. The first part is the "instant compression" which occurred simultaneously with the increase in effective pressure and caused a reduction in void ratio until an equilibrium value was attained at which the soil supported the overburden pressure. The second component is the "delayed compression" which is the time-dependent reduction in volume at unchanged effective stresses. The element of time in the consolidation process is one that most distinguishes the consolidation behaviour of soils undergoing natural sedimentation and compression from those subject to laboratory consolidation.

In the absence of very long term field measurements of reductions in void ratio of soils represented by Figs. 4c and 4d both the rate and magnitude of their consolidation with time would be difficult to determine

"Quick clays"

Soils most commonly encountered in the field occur in either a normally or overconsolidated state. A group of late glacial marine clays peculiar to the Ottawa - St. Lawrence valleys of Canada and the coastal regions of Norway and Sweden, known as "quick clays" owing to their propensity to rapidly lose shear strength upon remolding, commonly have moisture contents close to or above their liquid limits. In relation to the natural loads to which they have been subject these clays may be shown to be either normally consolidated or overconsolidated. With respect to their field void ratio vs. depth relationships, however, they can be shown to be in a state of either delayed consolidation or underconsolidation compared with void ratio vs. effective stress relationship that would be produced from a laboratory test using rates of loading much more rapid than those to which the soils would be subject in the field.

Soil Loading by Sedimentation

An important consideration regarding the consolidation of soils is the rate at which the load of sediment is applied. For the example in Figure 4a, effective pressures, assuming a reasonable submerged unit weight of the soil of 7.48 kN/m^3, could range from 10 to 10,000 kPa corresponding to approximate soil depths of 1.33 to 1,337 meters. The rates at which the effective pressures will accumulate, however, will vary widely as a function of the rate of sedimentation.

Skempton (1970) lists rates of deposition for Quaternary and Pliocene argillaceous sediments as 0.008 - 0.120 mm/yr. For deltaic deposits, about 0.001 mm/yr. for shallow marine deposits, and 0.00003 mm/yr for deep sea marine deposits. Rates of sedimentation within the highly dynamic environment of fjords are given by Syvitski et al. (1986, p.137) as ranging from 0.1 to 9,000 mm/ yr. Given the range in sedimentation rates of at least 8 orders of magnitude as noted above it is evident that the rate of accumulation of sediment is strongly controlled by the environment of deposition.

On the assumption that the soils represented by the curves in Figure 4 were deposited in one of the more active environments of deposition such as a delta or fjord with a sedimentation rate of say 1mm/ yr an accumulation of 10m would require 10,000 years during which time the effective stress at the 10m depth would have increased from 0 to about 75 kPa - a relatively insignificant amount.

In southern Canada a period of 10,000 years is approximately equal to the length of post-glacial time. During this period, however, active sedimentation in the Champlain Sea probably occurred for about 2,000 years. Thus in order to accumulate 100m of sediment during that time it is apparent that an average rate of sedimentation would have been of the order of 50mm/yr. Such a rate of accumulation, while relatively high, would produce an annual rate of load increase of .0375kPa resulting in very low rates of consolidating stress and a limited amount of time for the consolidation process to occur.

Sedimentation Compression Relationships

A particularly useful review of the consolidation of clays by the progressive accumulation of sediment was published by Skempton, (1970). This work, which follows upon the concept of sedimentation compression relationships described by Terzaghi, (1941), was confined to normally consolidated clays.. A total of about 20 Pliocene or Quaternary clays of marine or fresh water origin from many parts of the world were included in the study. Sedimentation compression curves were prepared for each of the clays and these were plotted on the void ratio vs. log effective pressure diagram as shown in Figure 5. It was noted by Skempton that the void ratio of a normally consolidated clay at a given overburden pressure is dependent upon the amount of clays minerals present as indicated by the liquid limit. Using liquid limit values of 30, 50, 90 and 140 Skempton defined the boundaries between clays of low, medium and high plasticity respectively. He also plotted the points for the clays in terms of liquidity index rather than void ratio vs. log of effective pressure and found the plot to be confined within a narrow band of decreasing liquidity index with increasing effective stress. Only clays of high sensitivity and occurring at depths less than 3m had liquidity indices greater than 1.

Although the sedimentation compression relationships described above pertain only to normally consolidated clays they do provide a frame of reference for void ratio, hence water content, vs. depth relationships within which an evaluation can be made of the consolidation state of any soil if its water content, Atterberg limits, depth and overburden pressures are known.

Variation in Field Moisture Content with Time

It is evident from the above discussion that the moisture content of a soil in the process of sedimentation may decrease with time. Following uplift of the sediment from a subaqueous to a subaerial environment it is likely that further reductions in moisture content can occur as different hydraulic gradients and drainage paths are established. In the unsaturated (vadose) zone above the water table seasonal variations in field moisture content can be expected and for those soils containing significant amounts of expandable-lattice clay minerals alternate swelling and shrinking of the soil can occur as the moisture content changes. For soils that remain within the zone of saturation below the lowest level of seasonal variation of the water table it seems probable that the moisture contents, which may vary with depth, will be essentially constant over relatively long periods of time for any particular depth provided the soil is not subject to some natural or imposed change in the state of either effective or hydraulic stresses or both.

In the case of "underconsolidated" soils that have moisture contents in excess of that which might be expected for their given level of effective stress it would appear that the potential for some degree of time-dependent moisture reduction exists. Such a reduction in moisture content may in fact be ongoing in these soils but under hydraulic gradients that may well be too low to be detectable by even very sensitive field measuring equipment.

Geological History of Champlain Sea Sediments

The Ottawa - St. Lawrence Lowlands contain an abundant legacy of landforms, geological features and materials that derive from the continental glaciation of the region during the Quaternary Epoch and from geological processes that were active during recession of the continental glaciers and during post-glacial time. Foremost among these features are the deposits of the Champlain Sea which extended from the Gulf of St. Lawrence westward to about the present location of Pembroke in the Ottawa valley (Fig.7). Marine fauna are common throughout the deposits and provide a means for establishing radiocarbon ages for the various strata and landforms. Thus, it has been possible to determine that the Champlain Sea existed during the period approximately 12.0 k to 10.0 k years BP (Fulton and Richard, 1987).

An extensive literature has accumulated covering the Champlain Sea and its sediments. Among the more prominent contributors to this literature is the work of Bentley and Smalley, (1978), Clark and Karrow, (1983), Elson and Elson, (1959), Fulton, (1987), Fulton and Richard, (1987), Gadd, (1986), 1990), Karrow, (1961), Kirkland and Coates, (1977), MacClintock and Stewart, (1965), Occhietti, (1989), Pair et al.,(1988), Quigley, (1980) and Torrance, (1988). This work has been more than sufficient to establish the time frame for the basin, its areal extent, the nature and general distribution of the sediments. Further, the work covers drainage of the basin, its uplift and replacement by the Ottawa - St. Lawrence drainage system.

Development of the Champlain Sea as shown in Fig. 7 was initiated with recession of the continental glacier from the lower St. Lawrence valley thereby enabling marine waters to transgress inland over a crustal depression bounded by the ice-covered Canadian Shield to the north and the mainly deglaciated Appalachian Highlands to the south. Prest (1970) and Clark and Karrow (1984) favour the origin of the Champlain Sea through the northerly retreat of the ice front in a "window-blind" fashion. An alternative mode of origin for the Champlain Sea was proposed by Gadd (1980) whereby, through a calving bay mechanism initiated in the Gulf of St. Lawrence, the Champlain Sea extended progressively westward up the Ottawa Valley rather than continuing westward up the St. Lawrence valley. This hypothesis was proposed in order to accommodate the interpretation of radiocarbon dates on marine shells near the marine limit in the upper St. Lawrence Valley that are younger than similarly positioned radiocarbon dates in the Ottawa and Gatineau Valleys.

On the basis of visual examination of a substantial number of cores of Champlain Sea deposits obtained throughout the Ottawa valley from above Pembroke to Hawkesbury Gadd (1977) interpreted the sediments of the basin within this area to have been deposited in four environments. These environments were in ascending order of deposition: 1.) similar to those of a freshwater glacial lake; 2.) deep-water quiescent marine basin or pro-delta environment; 3.) bottom-set facies of a prograding delta; and 4.) upper delta facies of a prograding delta. In a continuing work on the same suite of cores Gadd (1986) further developed an interpretation of the origin of Champlain Sea sediments as the result of offlap of a sea which produced a suite of sedimentary environments. These environments in ascending order are:

Prodelta deposits - varve-like rhythmites that grade upward into massive blue-grey marine clay.

Delta front deposits - rhythmically stratified clay-silt with increases upward in the suite of silt-sand.

Delta top deposits - mainly silt-sand deposits displaying open channel structures.

Fluvial deposits - sand and silt derived from erosion and deposition of older basin sediments.

Within this suite of sediments Gadd (1986) observed two trends in grain size gradation: 1.) vertical coarsening upward within each lithological unit and within the sediment body as a whole and 2.) a radial fining of sediment from the margin toward the centre of the basin. These interpretations are based on visual examinations of the sediment cores and are unaccompanied by information on sources of sediment and the location of primary and possibly secondary flow channels that contributed sediment to the basin.

The concept of a prograding delta developed with in a marine basin provides a model that may be applied to interpret the origin of Champlain Sea sediments. However, the relationships among the Champlain Sea basin, the Great Lakes basin to the southwest and the drainage of glacial Lake Agassiz to the northwest as well as the type of sedimentary model that best accommodate all geological aspects that bear upon the history of the Champlain Sea still remain to be fully resolved.

Regardless of its actual mode of origin it is apparent that the Champlain Sea, at least in its initial stages, occupied an ice-marginal position with the distance from the basin edge to the ice margin increasing with time as the continental glacier receded in a northerly direction. Thus, the Champlain Sea basin was a decidedly linear feature with the attributes of an extended estuary or perhaps a fjord.

The sequence of deposits found within the Ottawa River valley part of the Champlain Sea basin varies somewhat in lithology and thickness according to locality as reported by Gadd, (1986). In an earlier work Fransham and Gadd, (1977) compiled a composite stratigraphic section of the deposits as shown in Fig. 9 . This composite section, which has been modified herein to include a significant erosional surface between the marine deposits and overlying fluvial deposits, serves as the basis for separating the map units shown on Fig.8.

Glacial deposits that predate the Champlain Sea consist primarily of till upon bedrock and interlobate ice-contact sand and gravel such as those that extend from the mouth of the Gatineau River south through Ottawa continuing to the St. Lawrence River as portrayed by Gadd, (1987). Although flanked by Champlain Sea sediments in the Ottawa area, it seems most probable that these ice-contact deposits predate any of the Champlain Sea sediments.

The main deposits of the Champlain Sea, which rest upon fresh water deposits of varved clay, comprise massive and laminated layers of clay and silty clay commonly dark grey in colour. These deposits contain marine fauna and are interpreted by Gadd, (1986) as being of deep water marine origin. These strata are overlain by laminated clays and red and gray silty clays interpreted by Gadd as various delta facies resulting from a fluvial system that developed as the Champlain Sea basin was uplifted. In the deeper parts of the Champlain Sea basin, particularly east of Ottawa and north of the Ottawa River, thicknesses of up to 100m of the clays have been encountered in borings (Gadd, 1986).

Texture and mineralogy of Champlain Sea sediments

A detailed study of Champlain Sea sediments from boreholes in the Hawkesbury area of Ontario by Quigley et al.(1981, 1983) provides useful information on the texture and mineralogy of these deposits. In this area the percentage of clay-sized (<2µm) material in the soils ranges from 43 to 93 per cent with an average of 83 per cent. In terms of mineralogy, however, the clay size fraction consists of approximately 50 per cent quartz, feldspars, carbonate and amphiboles with the remainder consisting of illite, vermiculite and chlorite with minor amounts of swelling clay minerals and amorphous material.

In an excellent summary of previous work done on the mineralogy of Champlain Sea clays Torrance, (1988) concluded that the primary minerals comprising feldspar, quartz, amphiboles and pyroxenes constitute the majority of the soil with clay minerals and oxides rarely exceeding 30 per cent and generally much less than that amount. Even within the clay size fraction of the soil the primary minerals dominate. The mineral composition of the sediments is such as to clearly reflect the dominance of the Canadian Shield as the source area with till derived from Canadian Shield as the source material. Torrance also noted that within the Ottawa Valley sufficient work has occurred to be confident of the mineral suite present but not to be confident of the relative abundance of mineral species and its variation with depth and location.

Issues arising from the provenance of Champlain Sea sediments

Derivation of Champlain Sea sediments from tills of the Canadian Shield poses something of a problem as to the identification of the residual material that must exist following winnowing from the till of the fines that became Champlain Sea sediments. As shown in Figure 10 the grain size composition of till matrixes in the southeastern Canadian Shield (Vincent, 1989) generally contain less than 20% clay size material with less than 10% a more common component. The sand size fraction generally exceeds 50% and silt constitutes from 20 - 50% of the total material. Champlain Sea sediments commonly have textures of 80% or more clay size material with the balance of silt and only minor amounts of sand. Thus, one unit volume of Champlain Sea sediment would require the clay component from at least four or more similar unit volumes of till although the silt component could be derived on a unit for unit basis. In any case the source areas of Champlain Sea sediments must contain extensive areas of sandy material that represent the residual from the production of the Champlain Sea sediments and which should be recognizable as a mappable surficial geological unit.

Location of the primary source of Champlain Sea sediment on the Canadian Shield to the north of the basin of deposition also creates some difficulty with the interpretation of the marine sediments as having been deposited as various facies of a prograding delta as proposed by Gadd (1977, 1987). Such a delta would presumably have migrated from west to east along the trend of the Champlain Sea with both the source of sediment and the water for transport also being to the west. It is difficult to reconcile this delta model with the evidence for sediment and meltwater sources to the north as well as the high probability of contemporaneous deposition of sediment throughout the length of the Champlain Sea basin which extended from near Pembroke in the Ottawa Valley to east of Quebec City.

Although the depositional model for the Champlain Sea basin may be open to question it does seem clear from the work of Gadd (1986) that the thickness of marine deposits in the basin can be in excess of 100 m. Accumulation of this thickness of sediment is indicative of a high rate of sedimentation of 50 mm/yr. or more. Such a sedimentation rate is contrary to the speculation of Quigley (1980) that sensitive sediments possessing a flocculated open structure, such as those of the Champlain Sea, are the result of a slow rate of deposition.

Possible influence of the proximity of the continental glacier to the consolidation of Champlain Sea sediments

The process of consolidation of sediments deposited in basins located either adjacent or proximal to the margin of a receding continental glacier could be subject to the influence of hydrostatic uplift pressures. Such uplift pressures, resulting from meltwater flow originating within the glacier that penetrates the substrate to emerge in the lower part of the basin, would counteract the submerged weight of the sediment and thus retard the rate of consolidation.

The potential hydrostatic head that could be generated within the glacier would be governed by the vertical profile of the ice mass which according to Paterson (1994) can be expressed by the parabolic equation:

$$h^2 = 2\tau_0 / \rho g \,(L - x)$$

where h is the vertical height (m) at a distance (L - x) (m) from the edge of the ice mass measured along a flow line, L is the distance (m) from the centre to the edge of the ice mass, τ_0 is the yield stress of the ice (kPa), ρ is the density of the ice (kg/m^3), which is assumed to be constant, and g is the acceleration due to gravity (m/s^2).

By using a median value of basal shear stress of 50kPa for glacier ice and values of ρ (920 kg/m^3) and g (9.806 m/s^2) Patterson (op.cit.) has rewritten the above equation as:

$$h = 3.4(L - x)^{1/2}$$

With the use of the above equation a probable ice front profile, such as the one shown in Fig.6, can be produced. At the ice front itself no additional increase in hydraulic head is generated. With increasing distance up a glacial flow line, however, the potential hydraulic head increases. For example, at a distance of 5 km up glacier from the ice front the ice thickness could be 240m which would have the potential to create an additional hydraulic head of 2.35 MPa at the base of the glacier if completely water-filled fractures fully penetrated the glacier.

Examples of the effect of high uplift pressures generated in the subsurface in proximity to the front of a continental glacier are given by Christiansen et al. (1982) in their explanation for the formation of Howe Lake in southeast Saskatchewan as a hydrodynamic blowout structure and by Clark et al (2000) in their discovery of meltwater in the Canadian Shield of the Northwest Territories that had been injected under high hydrostatic pressure into the subsurface during ablation of the Laurentide Ice Sheet around 10, 000 yrs. ago. These examples serve to illustrate the fact that continental glaciers can have produce significant hydrodynamic effects in the subsurface of areas adjacent to the glacier margin.

In the absence of specific information on the stratigraphy and permeability of the substrate, however, actual distribution of hydraulic heads within the receding glacier and lengths of flow paths between the glacier and the basin of deposition, the magnitude of possible uplift pressures within the basin of deposition cannot be determined. Further, with continuing recession of the glacier following initial sedimentation within the ice marginal basin the potential for the development of uplift pressures within the basin would diminish with time.

The series of glacial recession maps prepared by Dyke and Prest (1987), Fig.7, show that for the duration of the Champlain Sea in the Ottawa area, approximately 12,000 - 10,000 yrs. B.P., the continental glacier receded northward approximately 180 km. This amount of recession is equivalent to an annual recession rate of approximately 11 km per year. If this rate of recession occurred at a uniform rate and began at the margin of the Champlain Sea basin then in the first year of recession the ice margin would occupy a position 11 km north of the basin margin. Under these circumstances a flow path originating 1 km upglacier would have its gradient reduced from about 0.10 to 8×10^{-6}.

It can be determined from the profile of a continental glacier front, as shown in Fig. 6, that while the potential hydraulic head that can be provided by the glacier increases upglacier from about 100m at a distance of 1km from the ice front to 340m at a distance of 10 km the hydraulic gradient will diminish upglacier from 0.10 to 0.034 over this same distance. Thus, within the glacier the rate of head increase upglacier is accompanied by a similar rate of gradient reduction. As the glacier recedes from the margin of a basin of deposition, however, the length of any flow path originating anywhere within the glacier and terminating within the basin of deposition will also continuously increase resulting in even further reduction in the hydraulic gradient.

An assessment of flow path lengths and hydraulic gradients that may have arisen from the proximity of a continental glacier adjacent to the Champlain Sea basin leads to the following conclusion. Any uplift pressures that might have been generated in the depositional basin and which might have retarded consolidation of fine grained sediments would have been of modest magnitude, of brief duration and applicable primarily to the earliest sediments deposited.

Effects of post-glacial uplift of the Champlain Sea basin

Coincident with the northward recession of the Laurentide glacier the Champlain Sea basin was continuously uplifted by crustal rebound. During the active period of sedimentation into the basin the amount of uplift was approximately 135m (Fig. 11). Uplift of the basin caused saline marine waters to be gradually replaced by fresh water and the marine sediments were eventually exposed at surface. These uplifted fine-grained sediments were then subject to erosion as well as to fluvial and deltaic sedimentation associated with the development of the Ottawa River drainage system. With the continuation of crustal rebound during the post-depositional period the pore-water chemistry of the marine clays has been subject to substantial changes as a result of leaching of salts due to the infiltration and downward movement of precipitation.

In a study of the sensitivity of clays, primarily from the United Kingdom, Skempton and Northey (1953) concluded that the principal effects of pore water salt leaching from clays are: a.) reducing the liquid limit and remolded strength while leaving the water content and undisturbed strength unaltered and b.)increasing the liquidity index and sensitivity. Similarly, Torrance (1975, 1979, 1988) and Carson (1981) have undertaken extensive studies of the effect of leaching of pore-water salts on the geotechnical behaviour of Champlain Sea clays from the Ottawa valley. One of the important findings of this work is the decrease in remolded shear strength of the soil with decreases in pore-water salinity to the point that the soil may behave as a liquid when some low pore-water salt concentration is reached. Thus, the sensitivity of the soil is increased by leaching. Such an increase in sensitivity is, in effect, the result of a reduction in the value of the soils Liquid Limit without a reduction in the soil's moisture content thereby causing an increase in the Liquidity Index.

In early post-glacial time down cutting by the newly formed Ottawa River and its tributaries through the soft fine grained sediments of the Champlain Sea with their high water contents gave rise to extensive flow slides on terraces that had developed throughout the Ottawa River system. These early landslides, which appear to have been of the flowslide variety, now occur as faint scars on the upper terraces of the Ottawa River and are at least one, if not more order(s) of magnitude larger than any contemporary landslide scar. It is not known with certainty whether these early extensive landslides are attributable to the effects of post-depositional leaching of pore-water salt, lack of consolidation, high initial moisture contents, rapid drawdown by erosion, external loading by earthquakes or some combination of these and possibly other factors.

Recent work by Aylsworth et al., (2000) has been done on the ages of large landslides and the presence of severely disturbed terrain in Champlain Sea sediments in an area located south of the Ottawa River approximately 40 km east of the city of Ottawa. A clustering of landslides with ages of ca. 4550 yr B.P. along paleovalleys in the area suggests such widespread landsliding was triggered by a strong earthquake. Further, close to the landslide area extensive occurrences of very disturbed terrain in a flat erosional plain are characterized by deformed bedding and irregular subsidence. The cause of these terrain disturbances is also attributed by Aylesworth et al.(2000) to a large earthquake that occurred in the area ca 7060 yr B.P.

Moisture Content vs. Depth Profiles for Champlain Sea Sediments

Throughout the Ottawa valley and elsewhere in eastern Canada Champlain Sea sediments have been extensively sampled in the subsurface by means of borings. Information on water contents at various depths thus exists, but only a small part of the total is available as published information. Available information is not sufficient to form the basis for establishing a regional or other areal pattern of moisture content distributions with depth. This information, however, does serve to deformation but not to flow. As values of the Liquidity Index increase beyond 1, however, and upon remolding, sufficient moisture can be released from the soil to permit deformation by flow to occur. The relationship shown in Figure 20 is not definitive for any particular soil but it is indicative of the role that water content, particularly at levels beyond the liquid limit, has in contributing to high values of both liqidity index and sensitivity.

Further work on property interrelationships in sensitive clays with particular reference to sensitivity, liquidity index, and effective stress was undertaken by Houston and Mitchell (1969). With the use of available data for normally consolidated clays they developed a general liquidity index - effective stress - sensitivity relationship as shown in Figure 21. It is apparent from Figure 21 that among soils of varying sensitivity the following relationships can be established: 1.) for a soil of a given sensitivity the liquidity index decreases with increasing effective stress; 2.) at a given level of effective stress sensitivity increases with increases in liquidity index; 3.) the similar slopes of the sensitivity contours indicate that the influence of effective stress on sensitivity does not vary greatly for different soils: 4.) sensitivities for soils with liquidity index values greater than 1 are in the range of an order of magnitude higher than for soils with liquidity index values in the range of 0 - 1; i.e. within the confines of the plasticity index.

Consideration of the role of effective stress creates greater complexity in the sensitivity - liquidity index relationship than that portrayed by Bjerrum (1954) as shown in Figure 20. Establishment of a definitive sensitivity - liquidity index - effective stress relationship for any specific soil would require a substantial amount of data specific to the soil in question. The relationships portrayed in Figure 21, however, are sufficient to demonstrate the role of water content in increasing values of liquidity index and sensitivity and reducing values of shear strength.

Houston and Mitchell (op.cit.) also examined the relationship between liquidity index and remolded shear strength for a number of clays. These clays, primarily of European origin, had a wide range of liquid limits. In a similar study Leroueil et al. (1983) used a cone penetrometer to determine the liquid limit and remolded shear strength (c_{ur}) of clays from eastern Canada including those from the Champlain Sea basin. From their experimental work they were able to demonstrate that on a plot of remolded shear strength against liquidity index within the range 0.4 to 3.0 their data plotted within a narrow band. A plot of these data as shown on Figure 22 is very similar to the results obtained from the earlier study by Houston and Mitchell. Through analysis of their data Leroueil et al. (1983) were able to express the relationship between remolded shear strength (c_{ur}) and liquidity index (I_l) as:

$$c_{ur}(kPa) = \frac{1}{\left(I_l - 0.21\right)^2}$$

It can be seen from Figure 22 that increases in liquidity index, hence water content, over the range of the plasticity index reduces shear strength of the remolded soil by about 2 orders of magnitude. Above the liquid limit, however, at which the remolded soil is essentially a slurry, a substantial increase in water content sufficient to produce a three fold increase in liquidity index results in a one order reduction in shear strength.

Permeability

One of the more important soil parameters to be evaluated for both geotechnical and hydrogeological studies is permeability which for a full range of soil types may have values that range over many orders of magnitude. For clayey soils permeability values are generally at the lower end of the value range but can also extend over five or more orders of magnitude.

In a study of the mechanisms controlling the permeability of clays Mesri and Olson (1970) noted the observation of Terzaghi more than 75 years ago of the importance of the nonuniformity of soil voids on clay permeability and of the dependence of clay permeability on the void ratio. It has been noted in a previous section of this paper that for fully saturated soils having a known specific gravity of soil solids a direct relationship exists between the void ratio and water content. Thus, water content values can serve as an indicator of the magnitude of permeability for specific soils.

In their study of the permeability of smectite, illite and kaolinite Mesri and Olson (op. cit) used mixtures of the clays with various polar and nonpolar fluids to produce slurries that were consolidated under low pressures in sedimentation tubes and then transferred to consolidation rings for consolidation in increments to high pressures. The permeabilities were calculated by fitting Terzaghi's theory of consolidation to the time-settlement observations. The data were plotted as the log of permeability against the log of void ratio. The data points for a particular combination of clay and fluid plotted close to straight lines with slopes of the lines and magnitudes of the permeability values dependent upon the clay/fluid mixture. In each case, however, the permeability decreased with decreasing void ratio hence increasing consolidation pressure. This study concluded that coefficients of permeability of clays are controlled by both mechanical and physico-chemical variables. Among the mechanical variables are size, shape, and geometrical arrangement of clay particles which influence the size of flow channels and the tortuosity of flow paths. Physico-chemical variables influence the permeability by controlling the tendency of the clay to disperse or to form aggregates. If aggregation occurs many very small flow channel form through which little flow occurs but the main flow occurs through a much smaller number of larger flow channels. Dispersion, in contrast, leads to formation of small flow channels of similar size which tend to reduce fluid flow.

Laboratory studies of permeability, such as those of Mesri and Olson referred to above, provide useful insights to the factors that influence evaluation of the coefficient of permeability. For practical purposes, however, such as addressing problems of groundwater flow or contaminant migration in porous media, slope stability or excavation drainage, understanding of the permeability of intact natural clays is particularly important.

A study of the permeability of intact soft clays mainly from the Champlain Sea basin region and elsewhere in eastern Canada but also from the United States and Sweden was undertaken by Tavenas et al. (1983b). This work provides particularly useful information on the relationship between *in-situ* void ratio and *in-situ* permeability for these intact clays. With respect to the factors that affect the *in-situ* vertical permeability (k_{vo}) the study found the vertical permeability to decrease with the void ratio following a linear e vs. log k relation for homogeneous clays with uniform grain size and mineralogy. This relationship applied only to clays within a specific geological environment as shown in Fig. 23 for Champlain Sea clays. A trend toward reduction in permeability with decreasing void ratio is evident for the Champlain Sea clays. It is also evident that for any void ratio, particularly above values of about 1.0, permeabilities may range over one order of magnitude.

Tavenas et al. (1983b) also determined that the plasticity index and clay fraction (CF) were significant parameters in determining the magnitude of the coefficient of permeability. From an analysis of their data for all of the clays studied they found that the void ratio - permeability relationship curves were well ordered according to the empirical parameter I_p + CF. Permeability - void ratio curves for selected values of (I_p + CF) are shown in Fig. 24.

Other findings of the study by Tavenas et al.(op.cit.) are that anisotropy is not a significant feature of the *in-situ* permeability of massive marine clays and that none of the previously reported permeability /void ratio relationships are valid regardless of the type of clay, initial void ratio, or range of void ratio change. A finding of their study of practical interest for clays with initial void ratios less than 2.5 and for volumetric strains likely to be encountered in engineering problems is the following linear relationship:

$$\lg k = \lg k_0 - \frac{e_0 - e}{C_k}$$

in which C_k is the permeability change index. The index C_k is defined as the slope of the *e* vs.log *k* curve for volumetric strains less than 20%.

For clays within the range of initial void ratios of 0.8-3.0 Tavenas et al. found a simple linear relationship between C_k and e_0 that can be expressed as:

$$C_k = 0.5e_0$$

The linear relationships expressed above along with the permeability - void ratio relationships shown in Figures 23 and 24 provide a means for estimating the permeability of Champlain Sea clays on the basis of a known value of void ratio which can be derived from a water content determination. For other clays the applicability of these specific relationships would require verification. It can be anticipated, however, that for any particular clay its permeability will decrease in a systematic manner with a decrease in void ratio.

The Role of Water Content in the Regional Evaluation of the Stability of Slopes in Champlain Sea Clays

Failures of slopes along valleys eroded into Champlain Sea clays, particularly those involving regressive flow sliding, constitute one of the principal geological hazards that affect the Ottawa - St. Lawrence Lowlands. These failures have been occurring since post glacial time with some of the most areally extensive failures having occurred very early in that time period. While all of these failures have caused loss of property, some have tragically resulted in loss of both life and property. Flow slides are characterized by the rapidity with which they occur. Their regression normal to the slope, and commonly their extension along a slope may extend for hundreds of metres or more. These failures are also characterized by extensive discharge from the failure zone of highly mobile remolded soil, free water, and commonly large blocks of upright or rotated intact soil some of which may still have trees in place. Such failures are in great contrast with relatively simple slope failures in which limited regression of the slope occurs through failure of a single slice or perhaps several slices of limited extent both parallel with and normal to the slope face.

As a consequence of the potential hazard of landslides in Champlain Sea clays considerable effort, particularly over the past forty years, has been devoted by geotechnical engineers and geoscientists to the investigation of these landslide occurrences.. The focus of these investigations has been both the causes of individual flow slides and the development of methods for assessment of the extent of flow slide hazard on a regional basis. Examples of some of the regional studies are the work of Sangrey and Paul (1971), Mitchell and Markell(1974), Klugman and Chung (1976), Carson (1977, 1979), Fransham and Gadd (1977), Lebuis and Rissman (1979), Lebuis et al.(1983), Tavenas et al. (1983a) and Tavenas (1984). In addition, an important contribution to understanding of the role of groundwater in contributing to the instability of slopes in Champlain Sea clays has been made by Lafleur and Lefebvre (1980).

Prior to examining some of this previous work with the aim of highlighting the role of water content as a contributing factor to slope instability, it is useful to examine some of the relationships among the stratigraphy and geometry of a slope and geomorphic processes that bear upon slope stability. In this context it is instructive to recall the comment of Terzaghi (1950) that the principal causes of landslides are factors that either increase shear stresses upon the slope or decrease shear resistance within the slope.

As shown in Fig. 25 a rather simplified slope in Champlain Sea sediments generally comprises several layers. The uppermost layer (A), commonly about 3 m in thickness, may consist of sand, fissured clay or some combination of the two. The intermediate layer (B), consists of soft clay or interlaminated clay and silt probably of marine origin and which may have been subject to post depositional leaching. Thicknesses of the clay layer will vary from one locality to another and may range from a few meters to several tens of meters. It is these clays, particularly in the thicker sections subject to fluvial or other type of erosion at the toe of the slope, that are most prone to slope instability. The marine clays may be underlain by a granular drainage layer (C) and/or by varved clays, till and bedrock collectively designated as layer (D) in Fig.25. With respect to physical properties the upper layer (A) is characterized by higher shear strength due to desiccation and much higher permeability due to fissuring than the underlying clay layer (B). The basal drainage layer (C) where present and the lower layers of till and/or bedrock (D) also possess higher shear strengths than the clay layer. The permeability of the lower layers (D) also is such that in some places they may act as a drainage layer for the clay. In other locations the layers of till and/or bedrock may act as an impermeable boundary.

Lafleur and Lefebvre, (1980) have shown that if the ratio H_1/H (Fig.25), where H_1 is the depth from surface through the clay layer to the top of a lower aquifer or drainage layer and H is the slope height, is 1.0 or less downward flow gradients will prevail and the slope will be drained. If the ratio H_1/H is in the range of 1.0 to 2.0 upward flow gradients will occur in the toe of slope leading to decreased stability.

The presence of a relatively permeable layer overlying soft clay of very low permeability also contributes to slope instability through the application of the "reservoir principle" as defined by Denness (1972) as follows:

"that overall failure mechanism governing all types of landslide complex that degenerate more rapidly from their initial stages of failure in a relatively solid state to a more liquid or viscous state than would be the case if they were supplied only by runoff. The necessary conditions are that a permeable stratum, able to take in and discharge its water store rapidly, overlies a relatively soft and impermeable stratum. The effect of the available water is to permit the removal of soil from the slope as landslip or mud flow, so steepening and thereby generating further slips to renew the slope wastage."

In essence, the overlying permeable stratum allows water to be stored following precipitation and to be subsequently released to an underlying less permeable clay stratum at a steady rate over some period of time significantly longer than would be the case if the precipitation fell directly upon the clay with a much more rapid rate of runoff. With respect to the landslides along the south coast of England from which the reservoir principle was developed the geological materials involved are primarily Tertiary fine-grained sediments subject to softening and disintegration upon wetting. These materials and their reaction to accumulated moisture is quite different from that of the Champlain Sea clays yet there is an apparent commonality of cause of slope failures in both cases as a result of the presence of excess water above the materials subject to failure.

An indication of the probable application of the reservoir principle to slope failures in the Ottawa - St. Lawrence Lowlands is the observation of Lebuis et al.(1983) that over 60 per cent of the landslides in the central part of the St. Lawrence Lowlands occur during April and May coincident with the period of maximum snow melt, precipitation and runoff. Lebuis et al. (1983) also note that more than 80 per cent of the earth flows that occurred in their area of study were attributable to erosion along banks adjacent to bodies of water. A similar observation regarding bank erosion and small slope failures precursor to major regressive flow slides had been made earlier by Sangrey and Paul (1971) in their study of flowslides in the Ottawa area.

Saturation of the relatively pervious surficial layer, in addition to contributing to softening of slope materials, will also establish hydraulic continuity with the underlying saturated soft clay. As a result an increase in pore pressures can be anticipated within the clay. The greatest effect of any such increase in pore pressure will occur at the toe of the slope as the locale for maximum head differential within the slope and for possible uplift pressure. As noted above the potential for increases in pore pressures at the toe of the slope increase if a drainage layer is located below the elevation of the toe of the slope. Increases in pore pressures at the toe of the slope combined with excessive toe erosion occasioned by high levels of runoff from seasonal precipitation and/or snowmelt thus contribute to reductions in the stability of slopes and to their potential for failure

Other factors affecting slope stability.

Other factors that influence the stability of a slope, as shown in Fig. 25, are the slope height (H) and the slope angle (β). Although slope surfaces are seldom planar most slope surfaces can be approximated by a straight line. The relationship between slope angle and slope height for stable and unstable slopes in eastern Canada has been compiled by Tavenas,1984 as shown in Fig. 26. It is apparent from the height /inclination relationship for these slopes that slope inclination is the more critical of the two variables. With the use of the lower curve for threshold of slope instability as shown in Fig. 26 it can be shown that an increase in slope inclination from approximately 12 degrees to 22 degrees results in a reduction of stable slope height of approximately 25 m.

In a study of flow sliding in sensitive soils from the Champlain Sea region and elsewhere in Ontario and Quebec Mitchell and Markell (1974) adapted the concept of stability number (N_s) devised by Taylor (1937) as a graphical aid for the solution of slope stability problems. Mitchell and Markell (op. cit.) noted that for undrained failure to occur in the backscarps of a flow slide, which commonly have an inclination of 45 degrees or greater, the stability number $N_s = \gamma H/C_u$ in which γ is the unit weight of the soil, H is the slope height and C_u is the undrained shear strength of the soil, must generally be greater than the number 6. In an analysis of over 40 landslides involving earthflows and retrogressive flow slides they noted that the distance of retrogression increased in a parabolic manner with increasing values of N_s particularly beyond the value of 6.They also noted that regression distances were related to increases in the value of the liquidity index (I_L).

As a result of the analysis of the relationships among stability number, regression distance and liquidity index Mitchell and Markell (op. cit.) devised a dimensionless chart (Fig. 27) that could be used to predict slope regression if the elements of the stability number and the liquidity index for slope materials were known. The same dimensionless chart was reproduced by Tavenas et al.(1983a) but included an additional zonation of the chart based on soil sensitivity (S_t) derived from the work of Carson (1977) and (1979) which shows an increase in the regression distance/slope height relationship with increasing soil sensitivity.

While the stability number, liquidity index and/or soil sensitivity all have a bearing upon the extent of slope regression, each of these parameters is directly linked to the water content of soil to which they pertain. As shown in Fig. 19 the value of C_u decreases with increasing liquidity index, hence increasing water content. Thus, for a slope of a given height H and bulk density γ, the value of the stability factor N_s will increase with increases in water content of the soil. Similarly the values of the liquidity index (I_l) and sensitivity (S_t) will increase with increases in water content with consequent decreases in shear strength of the soil.

Since flow sliding and extensive slope regression are associated primarily with soft soils in the remolded state it is reasonable that a correlation can be made between remolded shear strength (C_{ur}) and regression distance. Such a correlation was made by Lebuis et al.(1983) which has been modified (Fig. 28) to include a correlation between C_{ur} and liquidity index calculated from a C_{ur} - I_L relationship for Champlain Sea clays given by Leroueil et al.(1983). It can be determined from Fig. 28 that significant flow slide retrogression begins with values of $I_L > 1.20$ and $C_{ur} < 1.0$ kPa.. This relationship had been previously identified by Lebuis and Rissman (1979). They also observed from their study of flow slides in Quebec that earthflows most commonly occur in rather silty sediments with a plasticity index of 5 to 25 and a liquidity index greater than 1.5. Tavenas et al.(1983a) reviewed the work of Lebuis and Rissman (op.cit.) and concluded that very large distances of retrogression occur only in clays with liquid limits less than 40 per cent. While this conclusion may be valid for silty sediments with a narrow range of plasticity it does not apply to all occurrences of flow slides. For example, the clays involved on the large flow slide of 1971 on the South Nation River to the east of Ottawa described by Eden et al. (1971) had a liquid limit of 70% and a liquidity index of 1.

The observation by Tavenas et al. (1983a) regarding the relationship among liquidity index, water content and regression distance identifies a limitation as to the usefulness of liquidity index per se as an indicator of potential flow slide regression. This limitation derives from the fact that soils with very different values for their plasticity index ($I_p = w_l - w_p$) can have the same value of liquidity index dependent upon the soil moisture content. It appears that soils having higher values of plasticity index are likely to contain higher clay mineral contents with consequent higher levels of shear strength in both undisturbed and remolded states.

Since liquidity index values > 1 denote soil moisture contents greater than the liquid limit the liquidity index is an indicator, but not accurate measure, of the amount of soil moisture available to contribute to the fluid state of the soil upon remolding. It can be determined from Figs. 12-17 that values for the plastic limit of Champlain Sea clays are commonly close to 25 per cent. Thus for a clay with a liquid limit of 40 per cent and a liquidity index of 1.2 the moisture content would be 43 per cent. Since this condition, as noted above by Tavenas et al.(1983a), is indicative of a threshold for flow sliding the relationship w/I_p (in this case = 2.87) in addition to liquidity index might be useful as an indicator of flow slide potential. A combination then of values of $w/I_p > 2.8$ and $I_L > 1.2$ as soil properties along with critical slope geometry could well be indicative of the possibility of flow slide occurrence and is further demonstration of the role of water content as an indicator of soil behaviour.

Four distinct criteria necessary for flow slide regression have been identified by Tavenas et al. (1983a) and reiterated by Tavenas (1984). These criteria are:

1. <u>There must be an initial slope failure.</u> It is assumed herein that such a failure, probably due to erosion at the toe of the slope and perhaps influenced by high pore pressures in the toe area, may immediately precede a regressive flow slide or have occurred at an earlier time leaving the slope in a condition of reduced stability and thus subject to failure by a subsequent trigger mechanism.

2. <u>There must be continued backscarp instability.</u> Since backscarps are generally steep (>45°) the stability criterion $\Upsilon H/C_u = 6$ will apply.

3. <u>The slide debris must have the ability to become remolded during the slide.</u> High value of soil sensitivity, high slopes with significant potential energy to contribute to remolding of the soil, liquid limit < 40% are contributing factors.

4. <u>The slide debris must have the ability to flow when remolded.</u> The debris must have a very low remolded shear strength (<1 kPa), hence high water content and not be subject to topographic

restriction to removal of debris from the area of failure.

It is evident from these criteria that water content of the soil is a critical factor with respect to the probability of flow sliding. Thus, a field program for acquisition of soil moisture samples and vane shear strengths, along with airphoto analysis and field observation and measurement of slope attributes could provide an effective and economical means for a regional evaluation of slope stability.

Conclusions

1. The potential for landslides in the Champlain Sea clays constitutes one of the principal terrain hazards affecting both property and life in eastern Canada..

2. Geotechnical interest in research on the behaviour of Champlain Sea clays appears to have declined since about 1980. However, the research publication record for the period 1965 - 1996 contains a substantial accumulation of information about the character and behaviour of these clays.

3. The water content of cohesive soils, such as Champlain Sea clays, is one of the most important index properties of the soil. The field moisture content of Champlain Sea clay in relation to the liquid limit of the clay and the value of the liquidity index for the clay can be important indicators of the geotechnical behaviour of the clay.

4. Newly deposited sediments in marine environments have water contents at or above their liquid limits and possibly as much as 1 - 8 times the liquid limit. With continuing sedimentation the water content of underlying sediments tends to decrease below the liquid limit.

5. Champlain Sea clays may exist in the field in an "overconsolidated" state due to removal by erosion of previously present superjacent sediment. Simultaneously, however, the same sample of soil may exist in an "underconsolidated" state because of a field moisture content in excess of the soil's liquid limit and in excess of the water content or void ratio of the soil that could be expected under a field equivalent magnitude of load applied during a laboratory consolidation test.

6. Following post-glacial crustal uplift of marine sedimentary basins, such as the Champlain Sea basin, leaching of pore water from the clays has the effect of reducing the liquid limit of the clay but without reduction in the field moisture content. The result is an increase in both the liquidity index and sensitivity of the clay.

7. "Quick clays" which have the propensity to rapidly lose shear strength upon remolding commonly have field moisture contents close to or above their liquid limits.

8. Sedimentation rates for Champlain Sea clays were probably of the order of 50mm yr^{-1}. While such rates are relatively high the rate of application of consolidating stress would have been relatively low with only limited time for these deposits to have become consolidated.

9. The proximity of an ice front of a receding continental glacier to an active basin of deposition, such as the Champlain Sea, could have had the potential to generate significant uplift pressures within

the sediments of the basin thereby retarding their rate of consolidation.

10. The actual mode of origin of the Champlain Sea basin remains to be resolved. However, the geometry of the basin is that of a decidedly linear feature with attributes of an extended estuary or perhaps a fjord.

11. Champlain Sea clays in the Hawkesbury area of Ontario have the percentage of clay-sized (<2µm) material in the soils ranging from 43 to 93 per cent with an average of 83 per cent. In most of the clays, regardless of texture, the majority of primary minerals are feldspar, quartz, amphiboles and pyroxenes with clay minerals and oxides rarely exceeding 30 per cent and generally much less than that amount. This texture and mineralogy of the sediments is common but not necessarily consistent throughout the basin.

12. The mineral composition of the sediments is such as to clearly reflect the dominance of the Canadian Shield as the source area with till derived from Canadian Shield as the source material.

13. Tills of the Canadian Shield that are the source for Champlain Sea sediments commonly have a matrix texture of greater than 50 per cent sand-sized material. Thus, winnowing of fine grained material from the till as a source for Champlain Sea sediments must have left extensive areas of sandy material in the source areas.

14. The depositional model for the marine component of Champlain Sea sediments whether as an eastward-directed prograding delta or as contemporaneous deposition into an ice-frontal estuary or fjord remains to be resolved. The latter model is more consistent with the source of sediment, source of water for sediment transport and distribution of sediments within the basin.

15. The probable average rate of accumulation of Champlain Sea sediments was of the order of 50mm/yr. Actual rates of sedimentation, however, may well have exceeded this rate.

16. Crustal rebound following deglaciation caused approximately 135m of uplift of the Champlain Sea basin. Such uplift enabled salts contained within the sediment's porewater to be leached thereby increasing both the liquidity index and sensitivity of the soil.

17. In early post-glacial time down cutting by the newly formed Ottawa River and its tributaries through the soft fine grained sediments of the Champlain Sea with their high water contents gave rise to extensive flow slides on terraces that had developed throughout the Ottawa River system. These early landslides now appear as faint scars on the upper terraces of the Ottawa River and are at least one, if not more, order(s) of magnitude larger than any contemporary landslide scar. It is not known whether these early extensive landslides are attributable to the effects of post-depositional leaching of pore-water salt, lack of consolidation, high initial moisture contents, rapid drawdown by erosion, external loading by earthquakes or some combination of these and possibly other factors.

18. Analysis of records of borings in Champlain Sea clays from eastern Ontario show that water contents below the desiccated crust generally do not decrease with depth and commonly exceed the Liquid Limit. Further these water contents tend to exceed those that would occur in a laboratory

consolidation test under applied effective stresses equivalent to those of field loading.

19. A mean value of 1.7kPa is the best estimate of the undrained shear strength c_u (in triaxial compression) of a soil when at the liquid limit. The shear strength at the plastic limit is 100 times that at the liquid limit. These values provide a means for estimating the shear strength of a soil if the Atterberg limits and field moisture content are known.

20. For soils of varying sensitivity the following relationships can be established: 1.) for a given sensitivity the liquidity index decreases with increasing effective stress; 2.) at a given level of effective stress sensitivity increases with increases in liquidity index; 3.) the influence of effective stress on sensitivity does not vary greatly for different soils: 4.) sensitivities for soils with liquidity index values greater than 1 are in the range of an order of magnitude higher than for soils with liquidity index values in the range of 0 - 1; i.e. within the confines of the plasticity index.

21. The relationship between remolded shear strength (c_{ur}) and liquidity index (I_l) can be expressed as:

$$c_{ur}(kPa) = \frac{1}{(I_l - 0.21)^2}$$

22. A trend toward reduction in permeability with decreasing void ratio is evident for the Champlain Sea clays. It is also evident that for any void ratio, particularly above values of about 1.0, permeabilities may range over one order of magnitude.

23. Anisotropy is not a significant feature of the *in-situ* permeability of Champlain Sea clays.

24. Permeability - void ratio relationships provide a means for estimating the permeability of Champlain Sea clays on the basis of a known value of void ratio which can be derived from a water content determination.

25. The principal causes of landslides are factors that either increase shear stresses upon the slope or decrease shear resistance within the slope.

26. Among Champlain Sea clays, the thicker sections that are subject to fluvial or other type of erosion at the toe of the slope, are most prone to slope instability.

27. For undrained failure to occur in the backscarp of a flow slide the stability number $N_s = \gamma H/C_u$ (in which γ is the unit weight of the soil, H is the slope height and C_u is the undrained shear strength of the soil) must generally be greater than the number 6. The distance of retrogression increases in a parabolic manner with increasing values of N_s particularly beyond the value of 6. Also regression distances are related to increases in the value of the liquidity index (I_L).

28. Dimensionless charts based upon relationships among stability number, regression distance, liquidity index and soil sensitivity have been devised to aid in the prediction of slope regression. The value of each of the parameters involved in these charts is dependent upon the water content of the soil such that increases in water content contribute to decreased slope stability.

29. A correlation can be made between remolded shear strength (C_{ur}), liquidty index (I_L) and regression distance. Significant flow slide retrogression begins with values of $I_L > 1.20$ and $C_{ur} < 1.0$ kPa.. Very large distances of retrogression occur only in clays with liquid limits less than 40 per cent. It is probable that such clays with relatively low values for liquid limits are characterized by high contents of clay-sized particles but very low contents of clay minerals.

30. The relationship w/I_p in addition to liquidity index might be useful as an indicator of flow slide potential. A combination of values of $w/I_p > 2.8$ and $I_L > 1.2$ as soil properties along with critical slope geometry could be indicative of the possibility of flow slide occurrence and which further demonstrates the role of water content as an indicator of soil behaviour.

31. Four distinct criteria necessary for flow slide regression have been identified:

1. There must be an initial slope failure.
2. There must be continued backscarp instability.
3. The slide debris must have the ability to become remolded during the slide.
4. The slide debris must have the ability to flow when remolded.

32. Water content of the soil is a critical factor with respect to the probability of flow sliding. Thus, a field program for acquisition of samples for soil moisture determinations, measurement of field vane shear strengths and airphoto analysis and field observation and measurement of slope attributes could provide an effective and economical means for a regional evaluation of slope stability.

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List of Illustrations

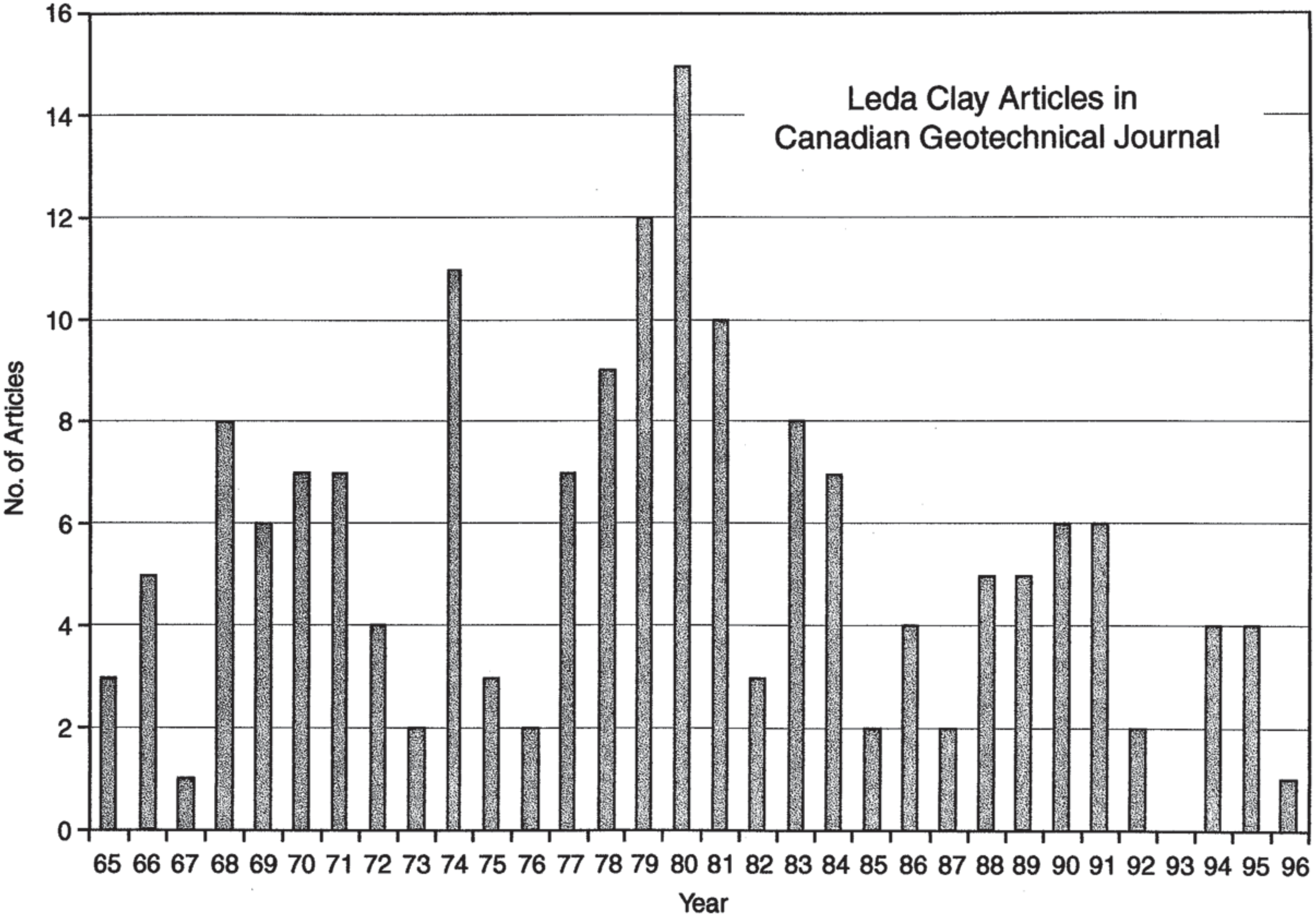


Fig. 1 Number of Leda Clay articles in Canadian Geotechnical Joural 1965-1996.

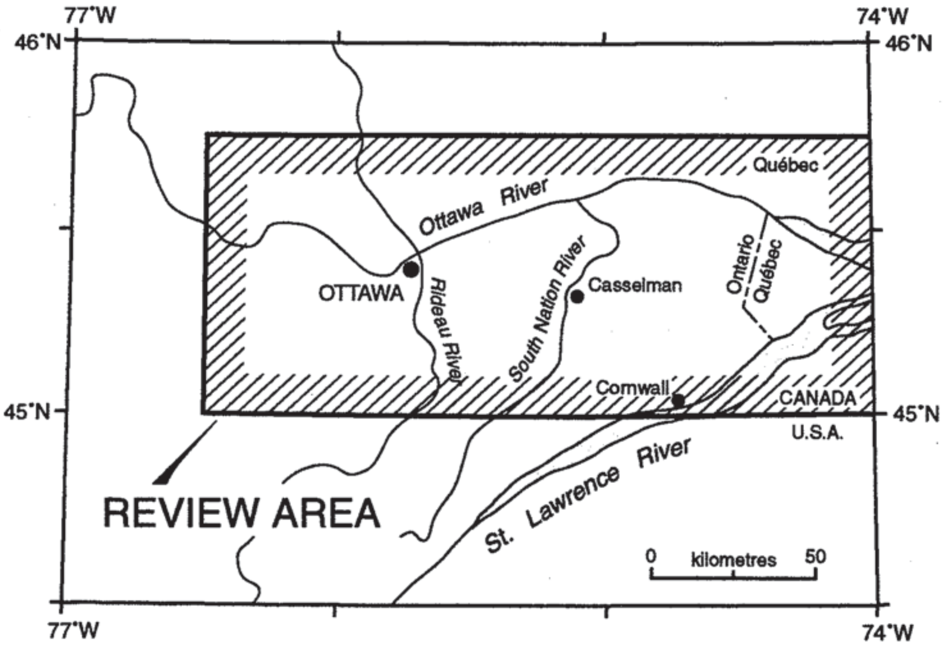


Fig. 2 Location of Review Area

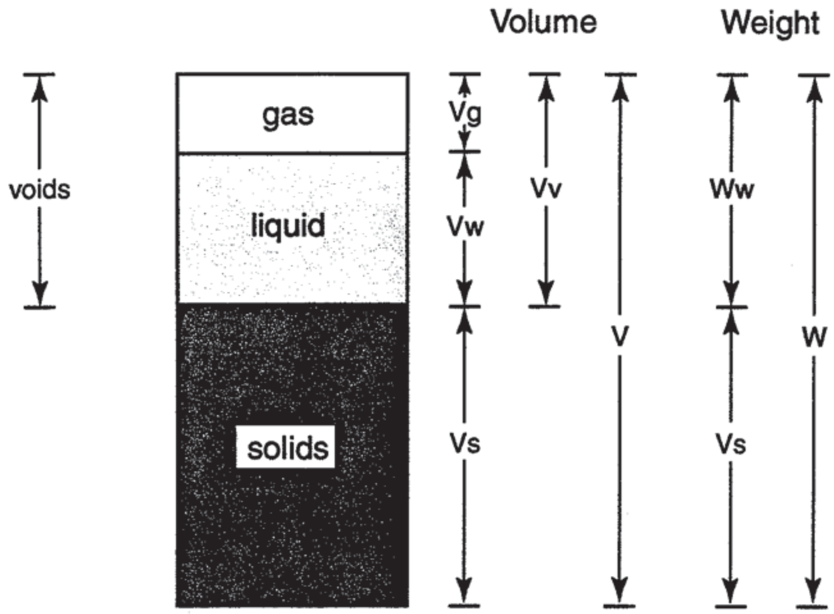
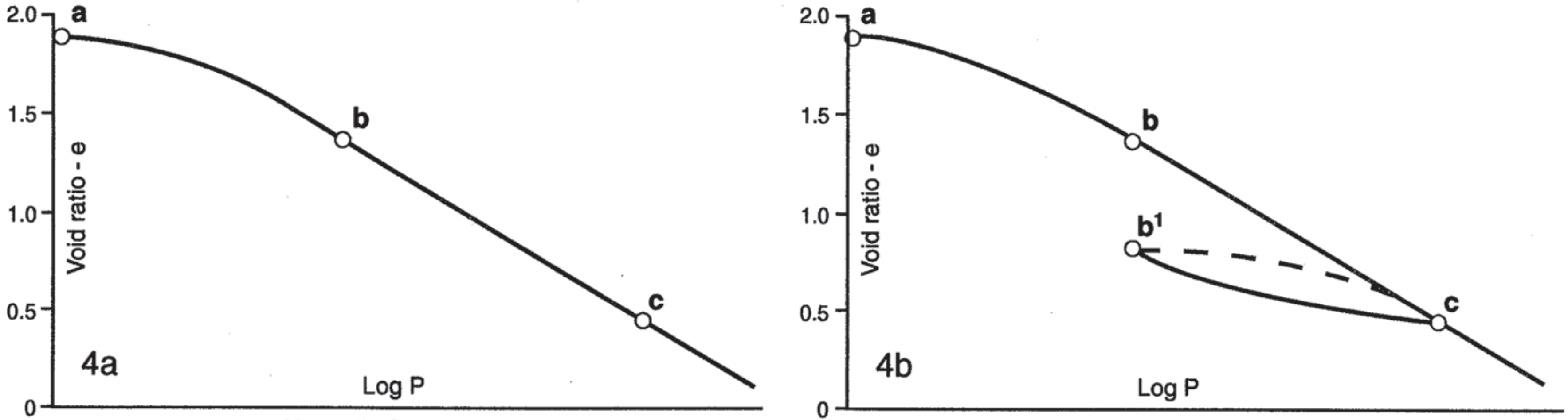
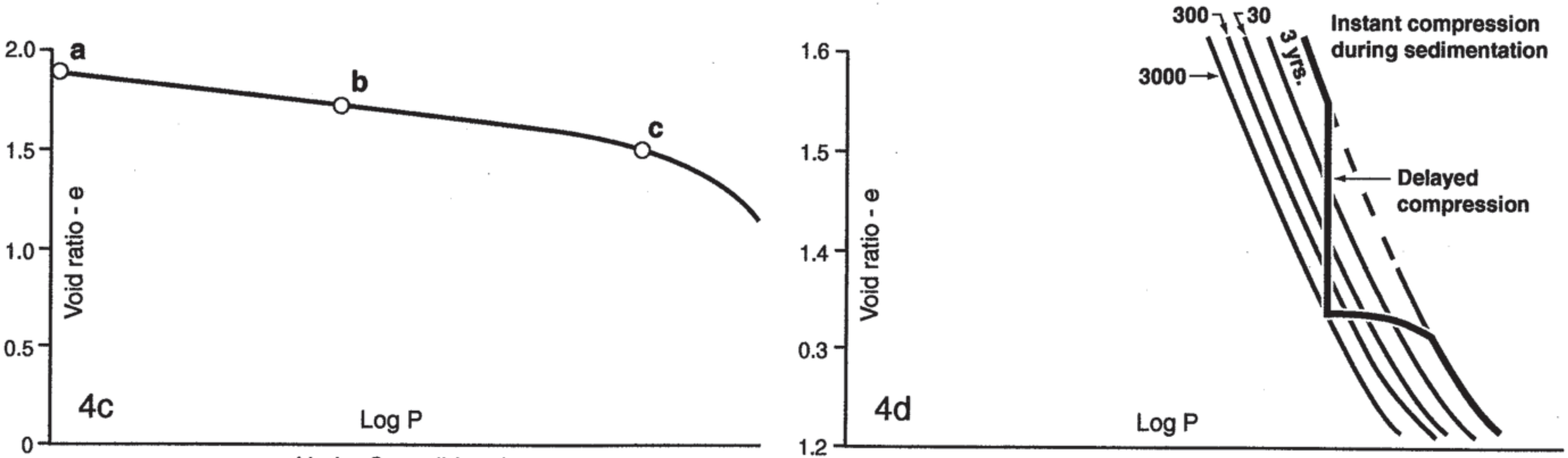


Fig. 3 Diagrammatic representation of weight/volume relationships for soils (after Peck, Hanson and Thornburn (1953))



Normally Consolidated

Overconsolidated



Under Consolidated

Delayed Consolidated (after Bjerrum, 1967)

Fig. 4 Consolidation states for soils

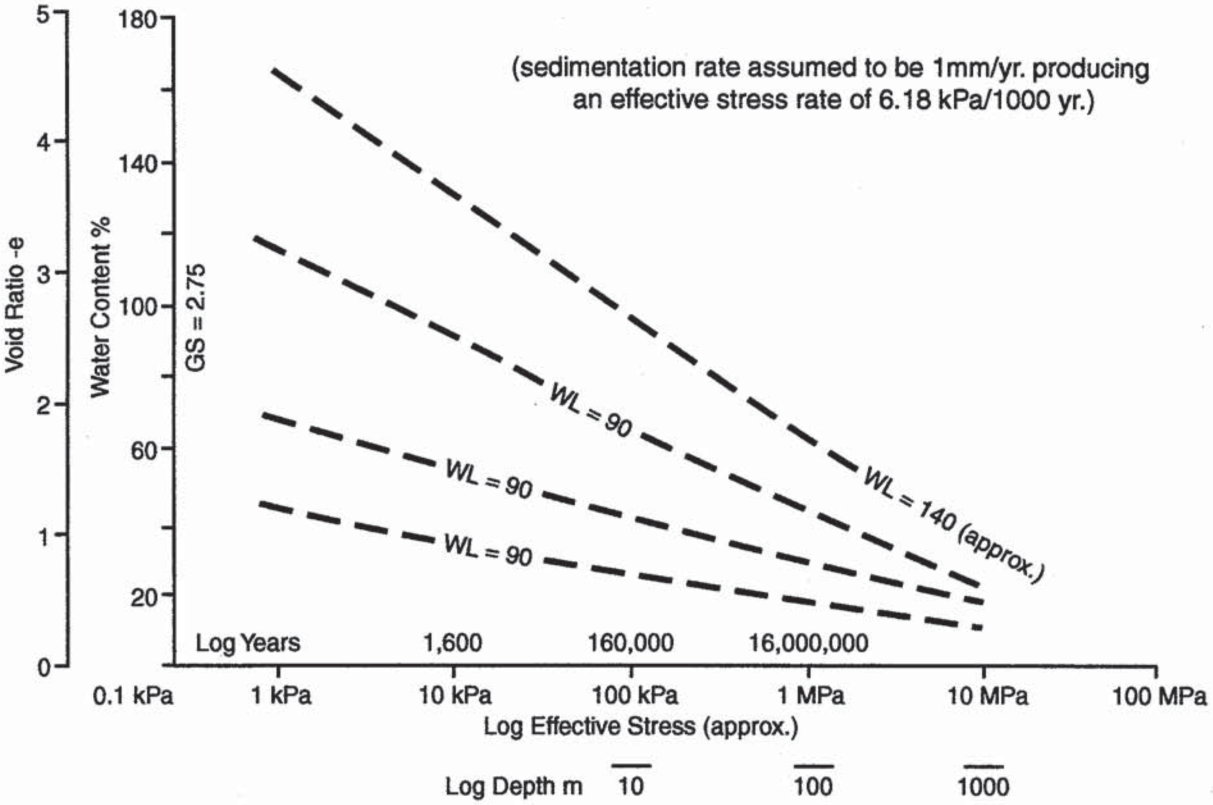


Fig 5 Sedimentation Compression Curves for Normally Consolidated Argillaceous Sediments (after Skempton, 1970)

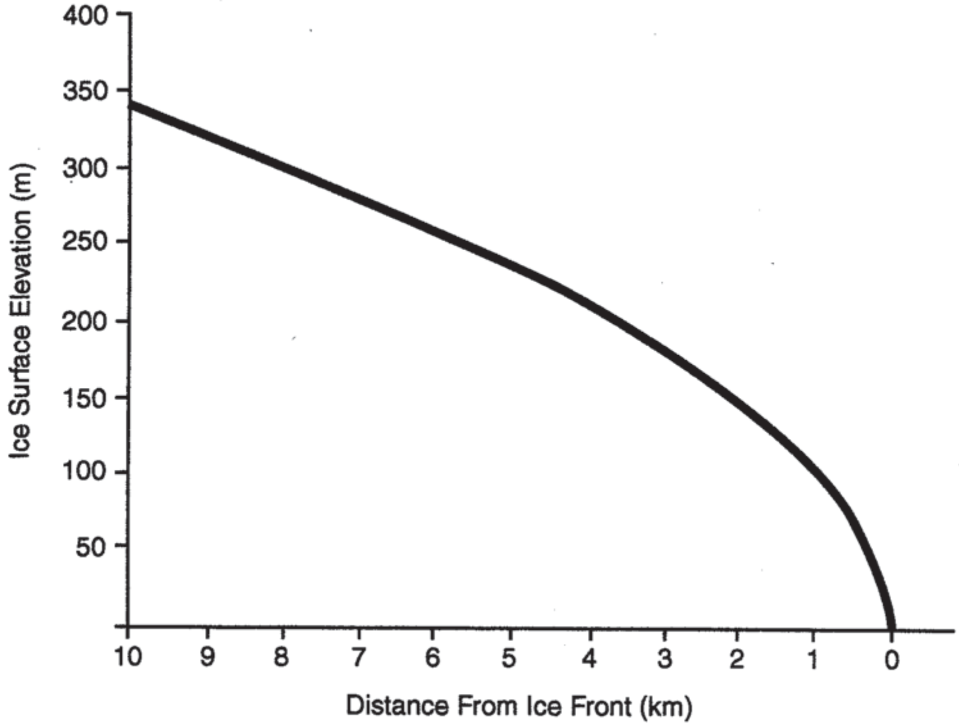


Fig. 6 Profile of continental glacier front

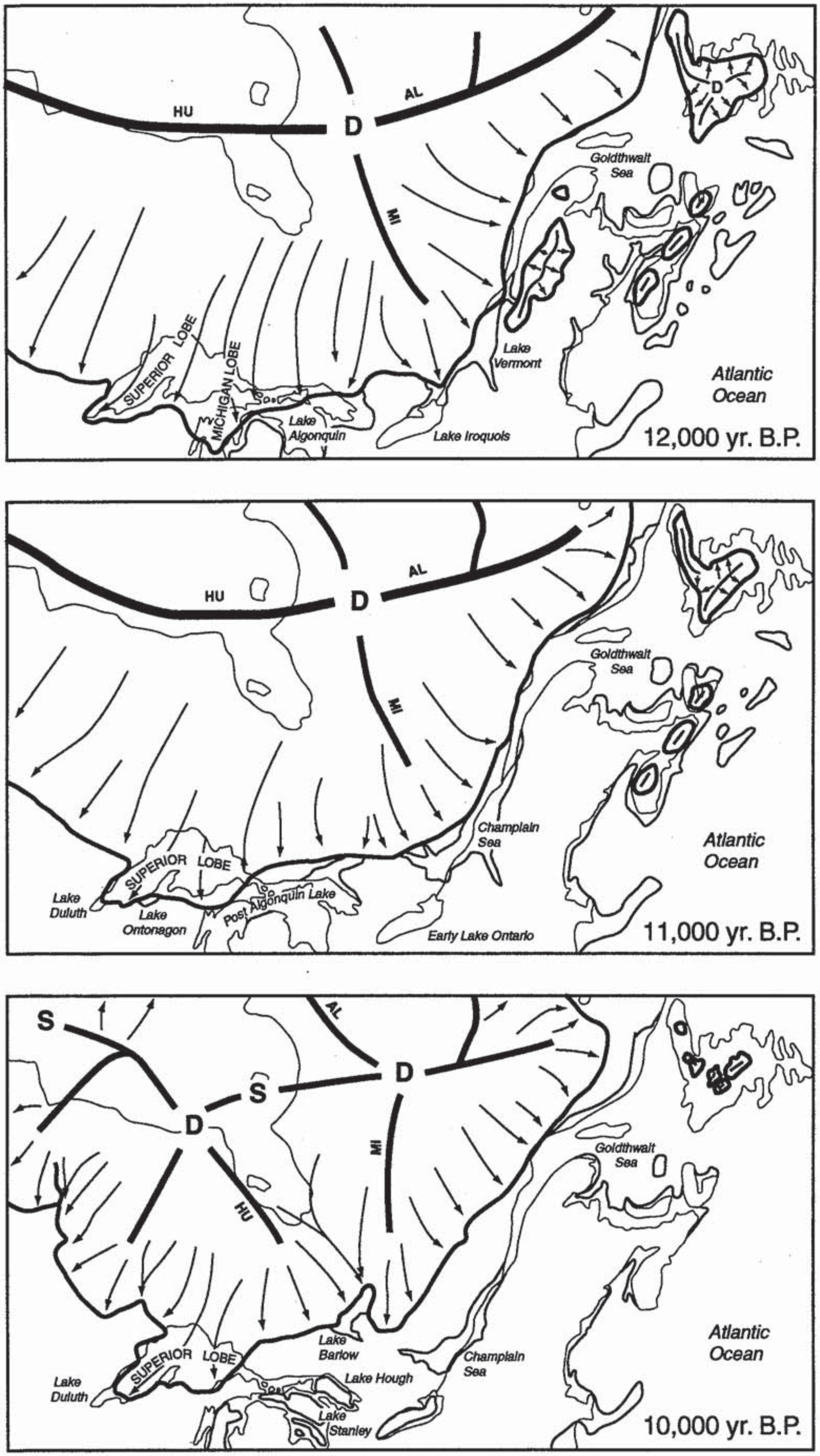


Fig. 7 Paleogeography of eastern Canada during the Champlain Sea episode. (after Dyke and Prest, 1987)

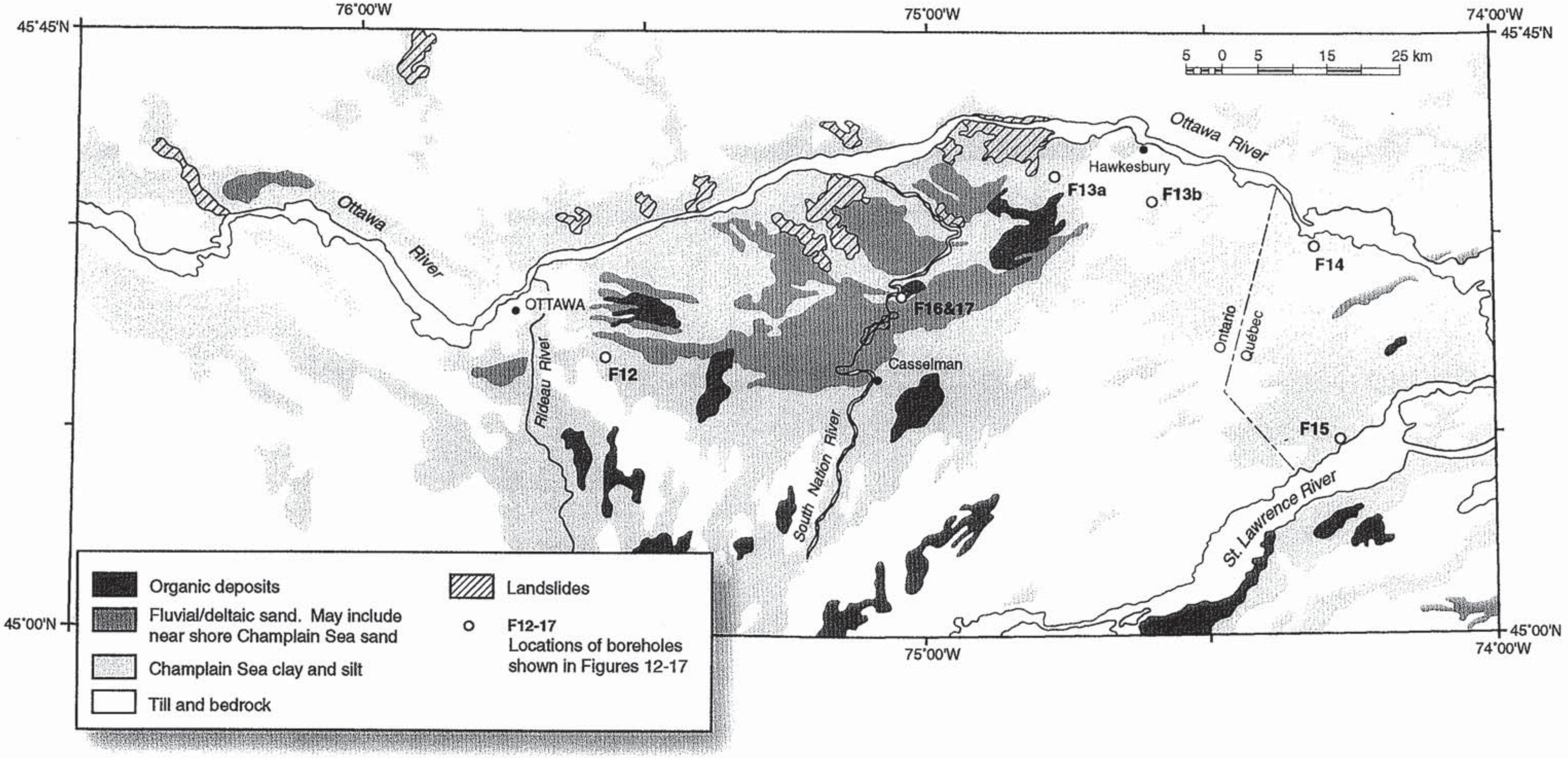


Fig. 8 Generalized distribution of surficial materials and landslides in the Ottawa valley. (after Fransham and Gadd, 1977)

Map Unit	Stratigraphic Unit
D	Organic Deposits
C	Fluvial - deltaic sand
▬▬▬	▬▬ Erosional Surface ▬▬
B	Clay and Silt
	Clay
	Deep Water Marine Clay
	Varved Clay
A	Ice Contact Gravel
	Till
	Bedrock

Fig. 9 Composite statigraphic section of Champlain Sea sediments in the Ottawa Valley related to map units. (after Fransham and Gadd, 1977)

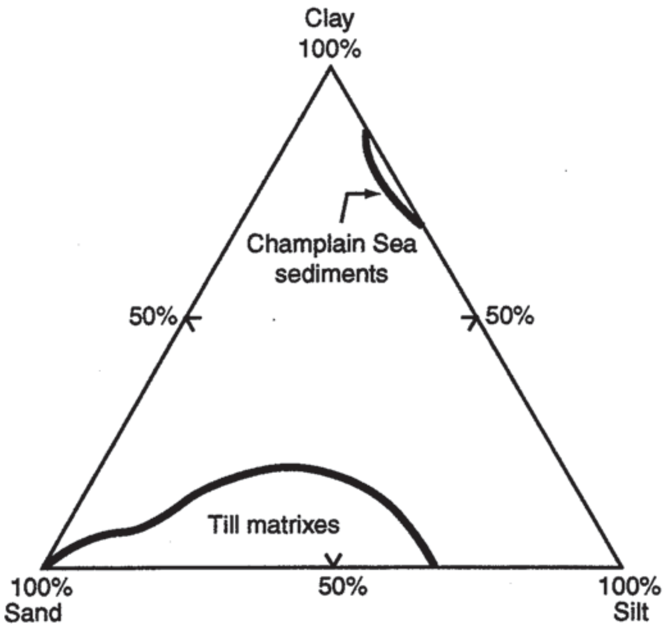


Fig. 10 Comparision of grain size composition of till matrixes in southern Canadian Shield with Champlain Sea sediments (after Vincent, 1989)

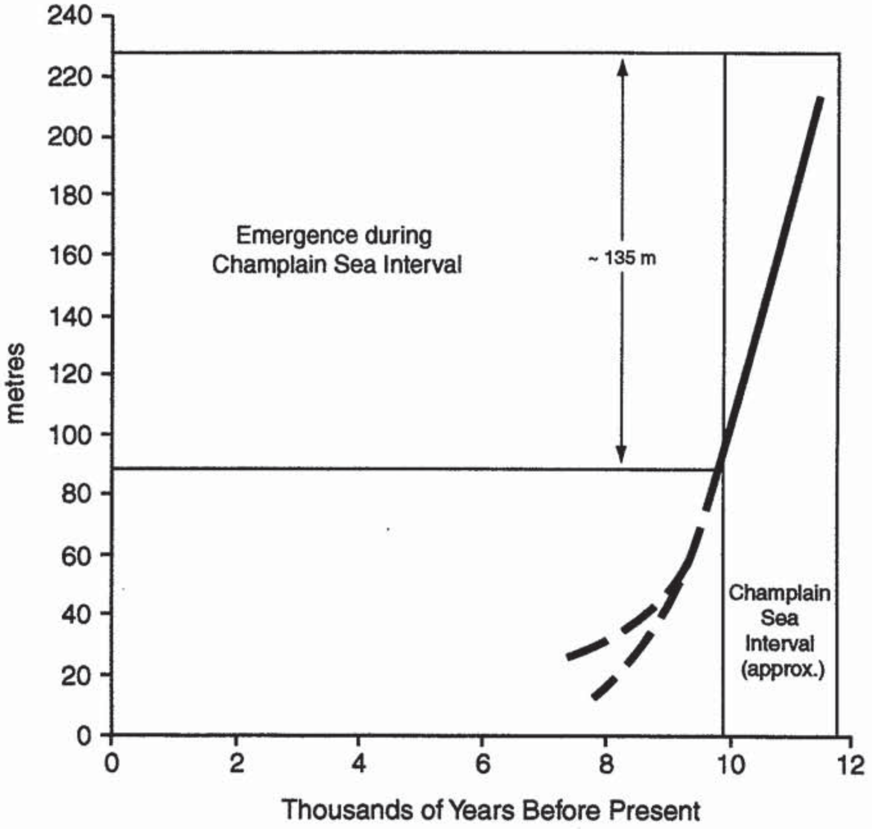


Fig 11 Emergence curve for the Ottawa Region (after Fulton and Richard, 1987)

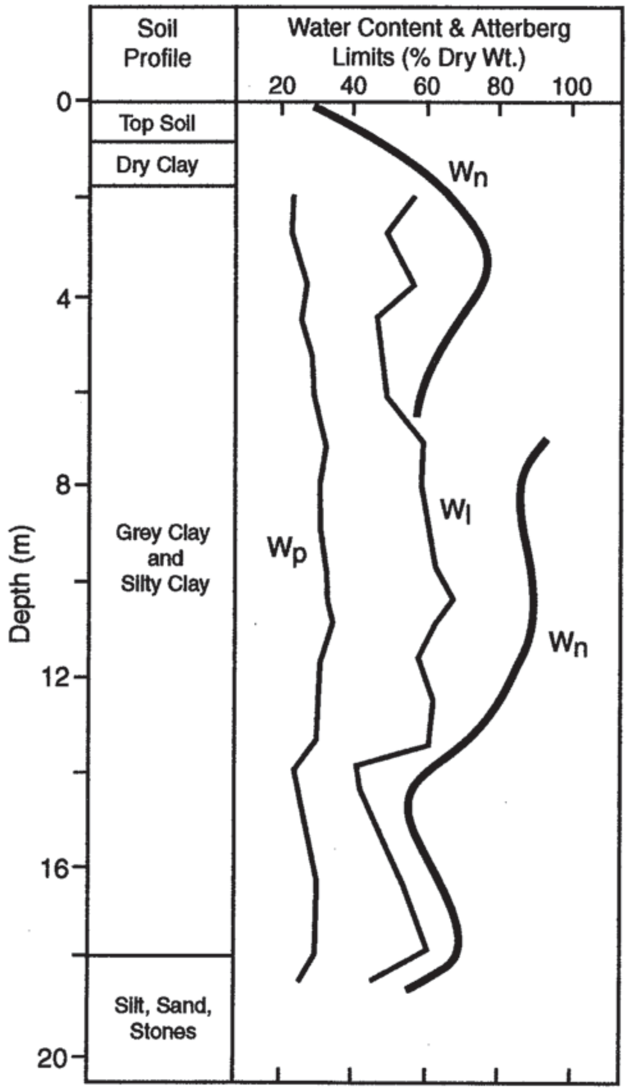
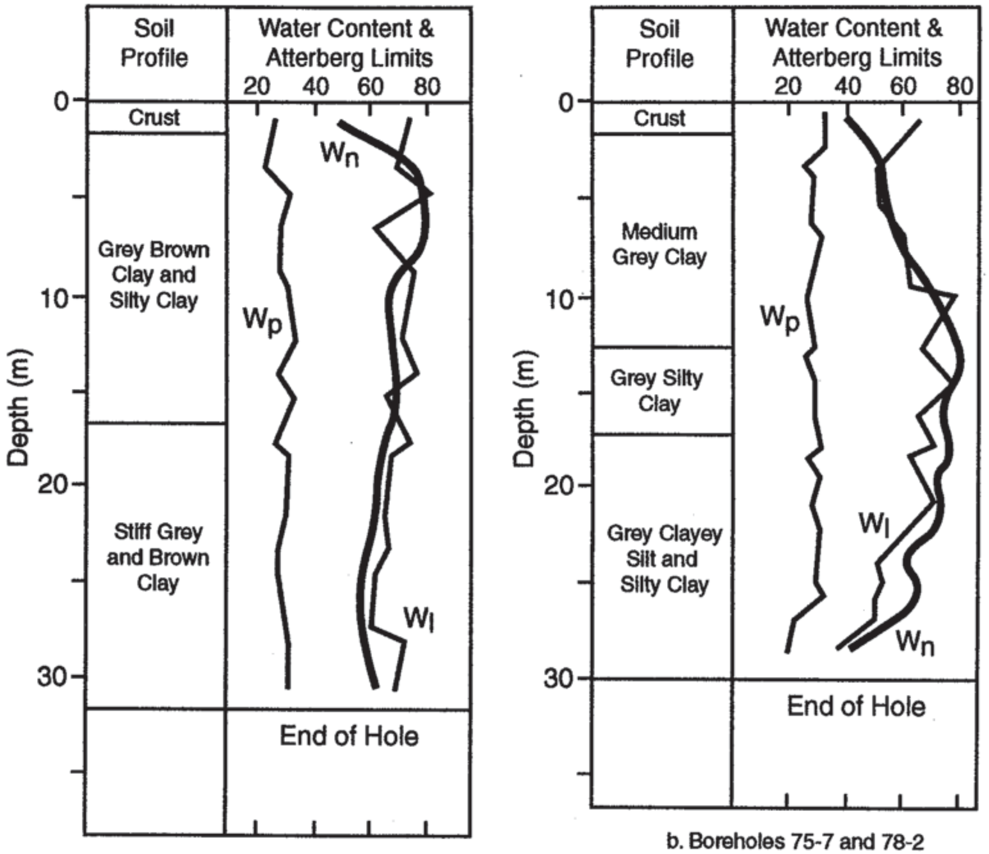


Fig. 12 Soil profile, Atterberg Limits, field moisture content of Leda clay at Gloucester, Ontario (after Lo et al. 1976)



a. Boreholes 75-2 and 78-1 (Lower-level clay plain)

b. Boreholes 75-7 and 78-2 (Upper-level clay plain)

Fig. 13 Soil profiles, Atterberg Limits, field moisture contents of Leda clay at Hawkesbury, Ontario (after Quigley et al. 1983)

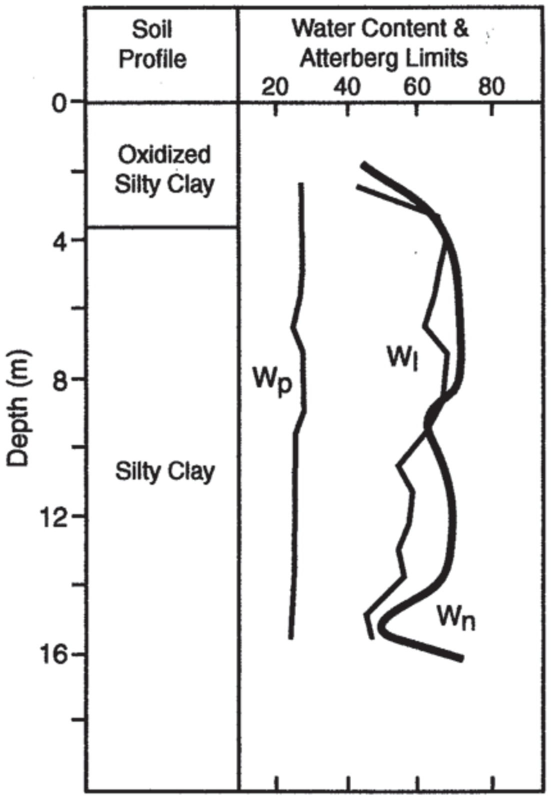


Fig. 14 Soil profile, Atterberg Limits, field moisture content of Leda clay at Rigaud, Québec (after Morin et al. 1983)

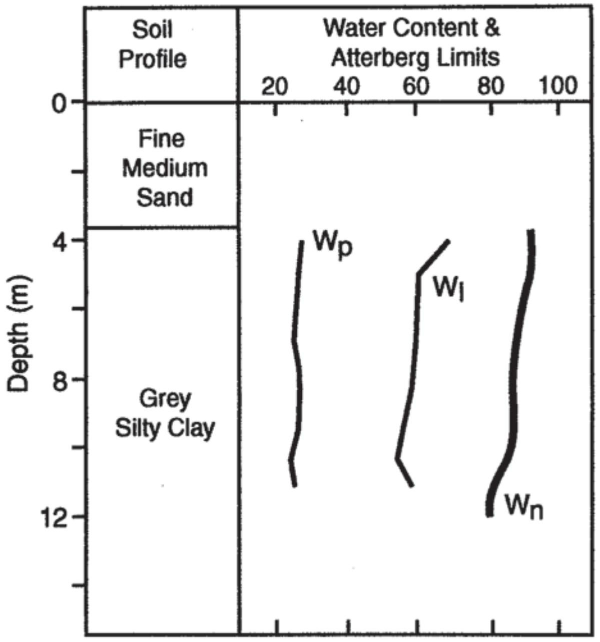
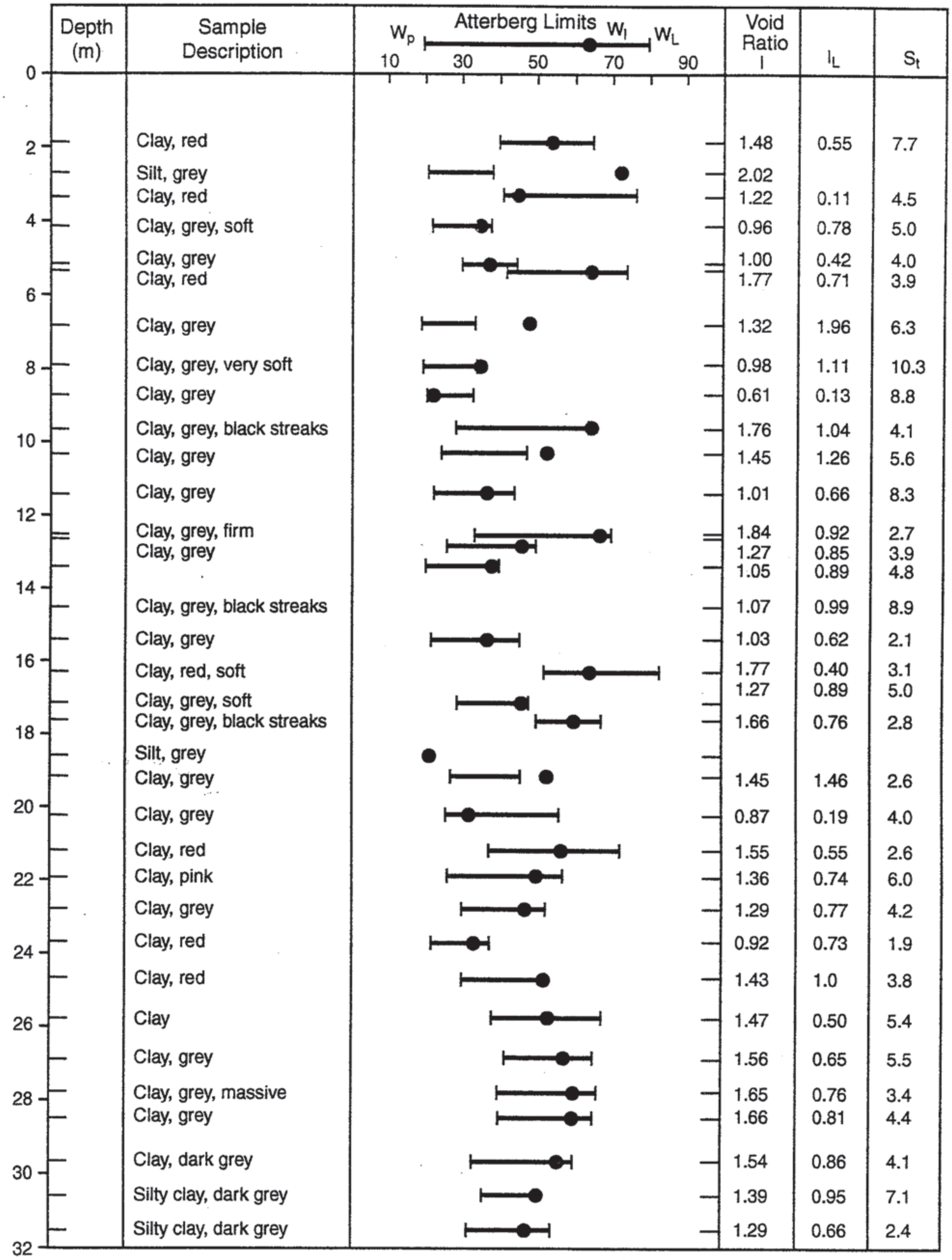


Fig. 15 Soil profile, Atterberg Limits, field moisture content of Leda clay at Chemin Ste-Catherine, Québec (after Morin et al. 1983)



Sample Description	Void Ratio l	I_L	S_t
Clay, red	1.48	0.55	7.7
Silt, grey	2.02		
Clay, red	1.22	0.11	4.5
Clay, grey, soft	0.96	0.78	5.0
Clay, grey	1.00	0.42	4.0
Clay, red	1.77	0.71	3.9
Clay, grey	1.32	1.96	6.3
Clay, grey, very soft	0.98	1.11	10.3
Clay, grey	0.61	0.13	8.8
Clay, grey, black streaks	1.76	1.04	4.1
Clay, grey	1.45	1.26	5.6
Clay, grey	1.01	0.66	8.3
Clay, grey, firm	1.84	0.92	2.7
Clay, grey	1.27	0.85	3.9
	1.05	0.89	4.8
Clay, grey, black streaks	1.07	0.99	8.9
Clay, grey	1.03	0.62	2.1
Clay, red, soft	1.77	0.40	3.1
Clay, grey, soft	1.27	0.89	5.0
Clay, grey, black streaks	1.66	0.76	2.8
Silt, grey			
Clay, grey	1.45	1.46	2.6
Clay, grey	0.87	0.19	4.0
Clay, red	1.55	0.55	2.6
Clay, pink	1.36	0.74	6.0
Clay, grey	1.29	0.77	4.2
Clay, red	0.92	0.73	1.9
Clay, red	1.43	1.0	3.8
Clay	1.47	0.50	5.4
Clay, grey	1.56	0.65	5.5
Clay, grey, massive	1.65	0.76	3.4
Clay, grey	1.66	0.81	4.4
Clay, dark grey	1.54	0.86	4.1
Silty clay, dark grey	1.39	0.95	7.1
Silty clay, dark grey	1.29	0.66	2.4

Fig. 16 Soil profile, Atterberg Limits, field moisture content of Leda clay from GSC borehole LV96-1 near Lemieux, Ontario

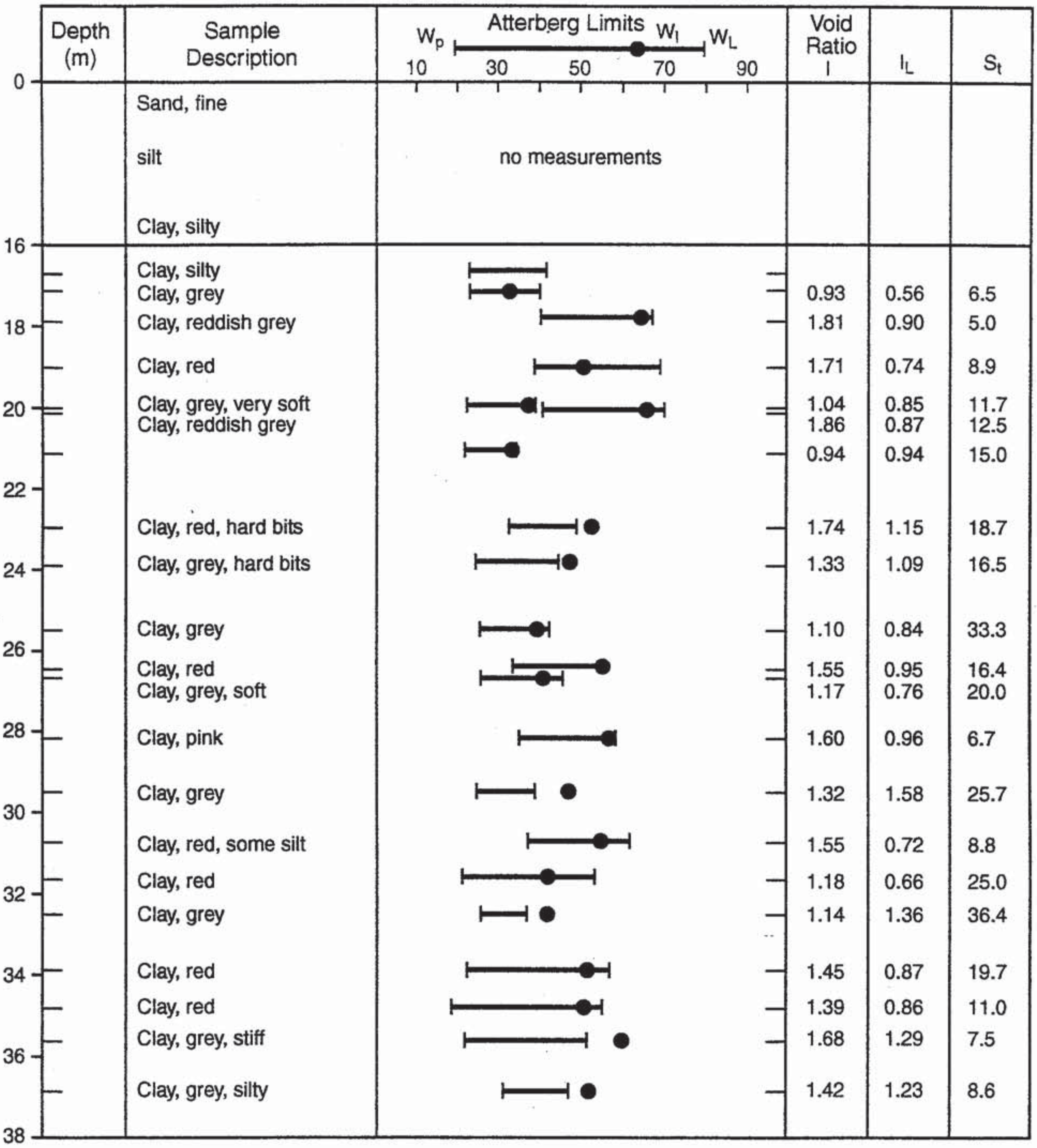


Fig. 17 Soil profile, Atterberg Limits, field moisture content of Leda clay from GSC borehole LV96-2 near Lemieux, Ontario

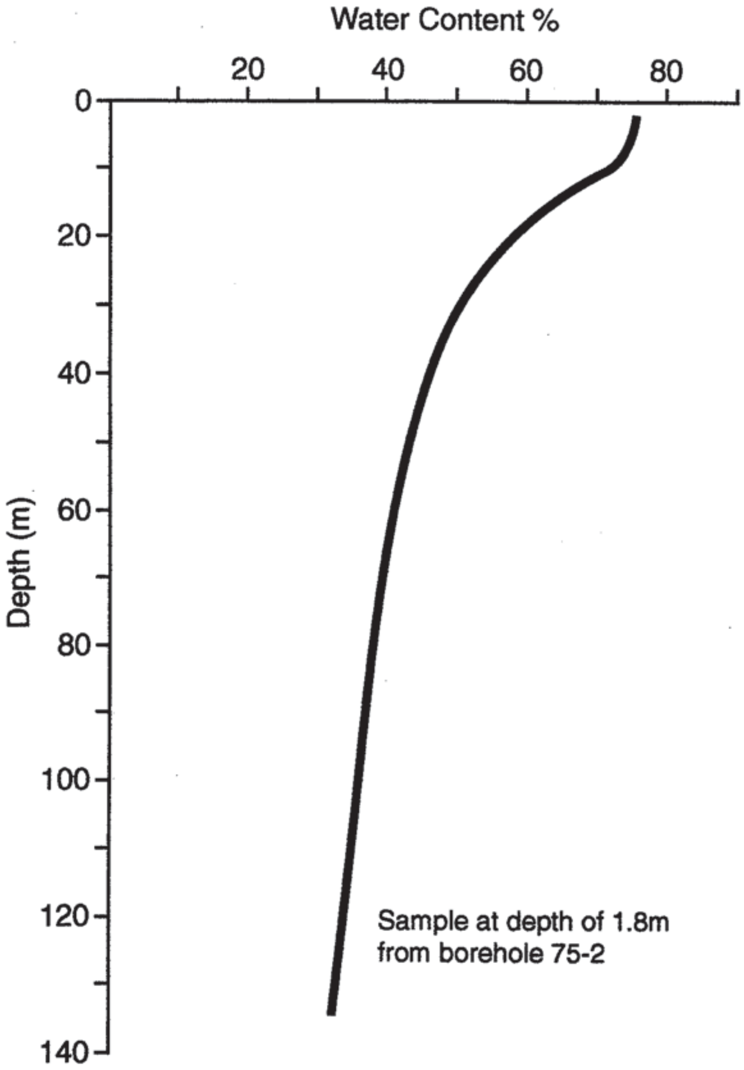


Fig 18 Water content vs. depth profile calculated from consolidation test data (from Quigley et al. 1981)

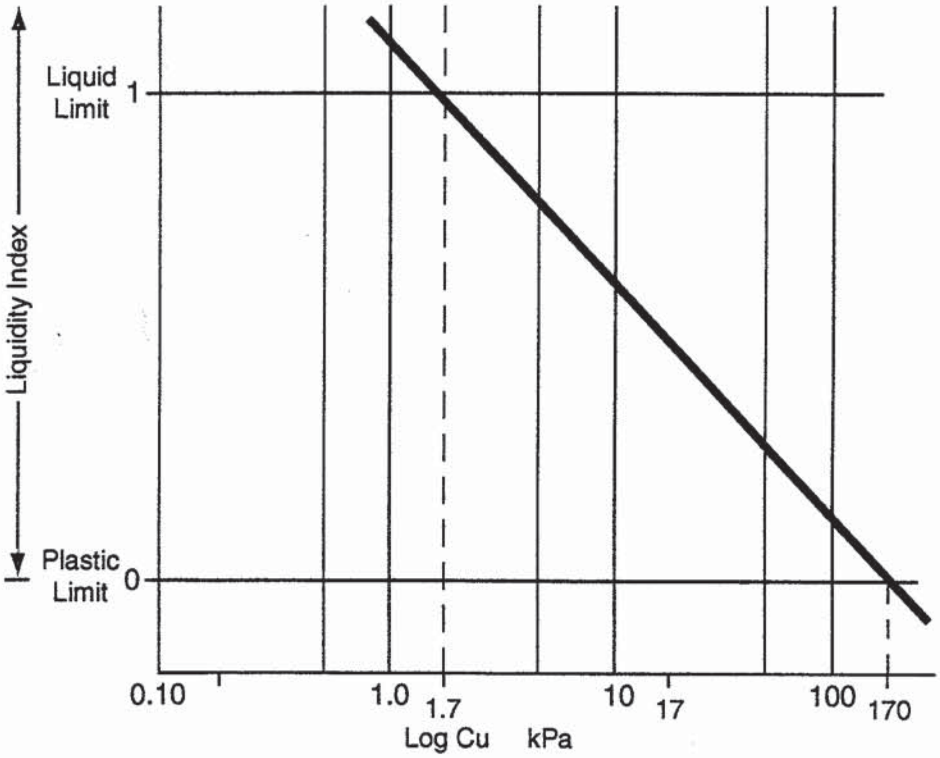


Fig. 19 Relationship between liquidity index and shear strength (after Wroth and Wood, 1978)

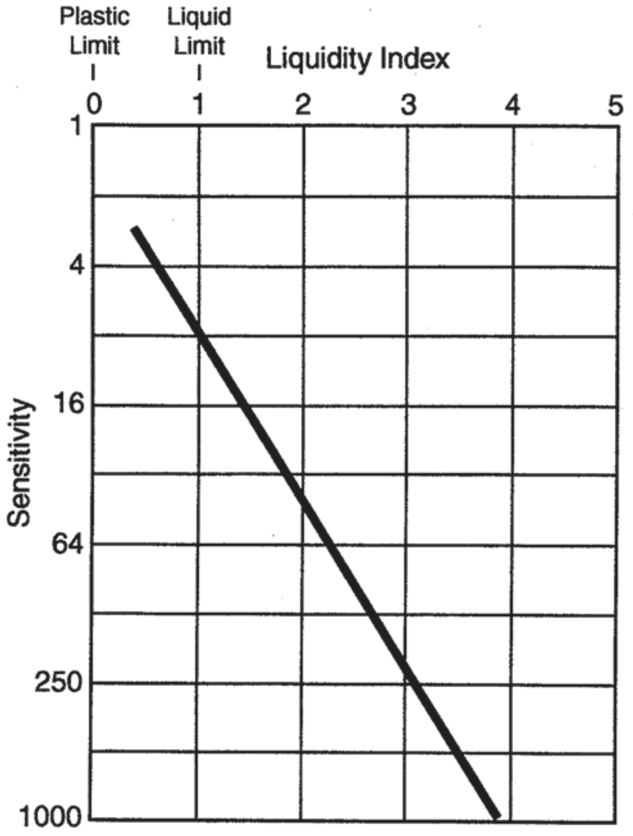


Fig. 20 Relation between sensitivity and liquidity index (after Bjerrum, 1954)

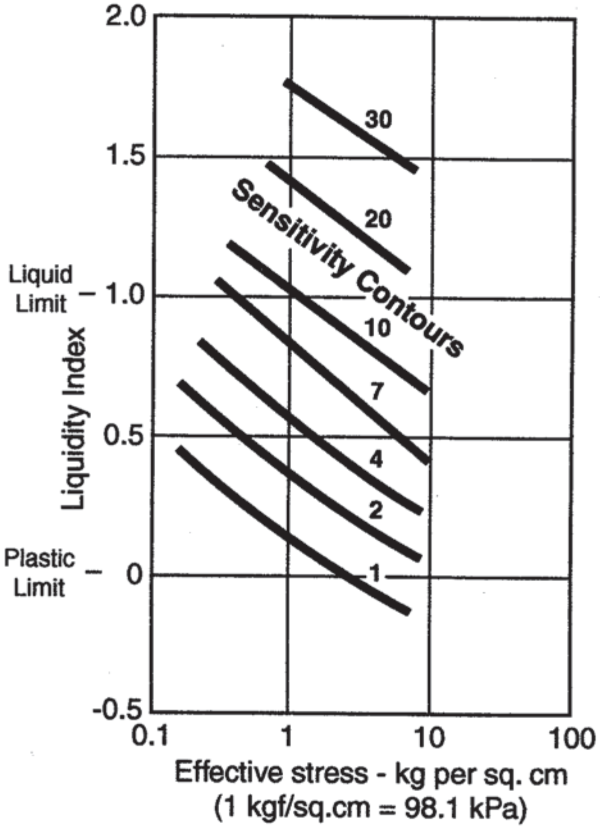


Fig. 21 General relationship between sensitivity, liguidity index and effective stress (after Houston and Mitchell, 1969)

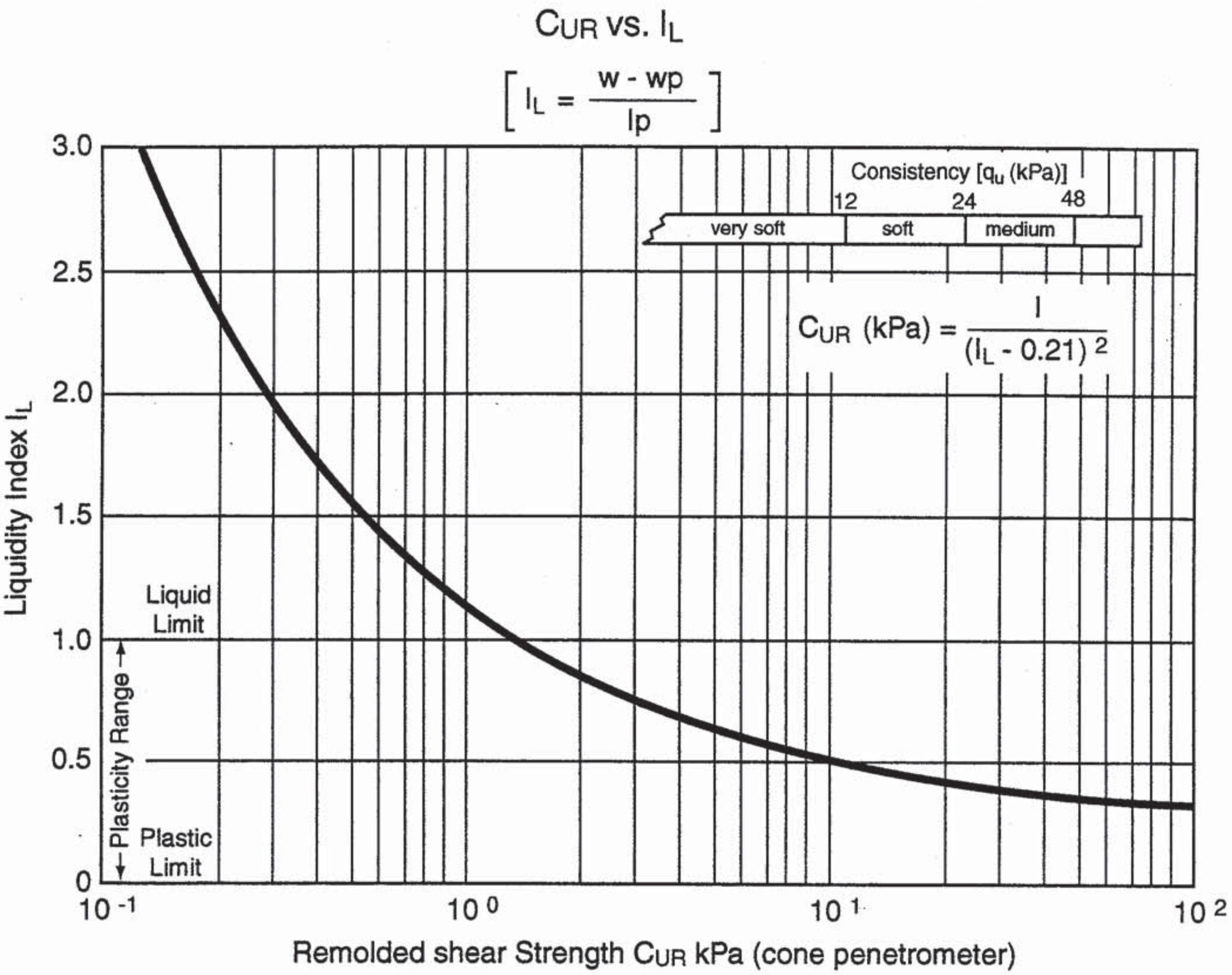


Fig. 22 Relationship between liquidity index and remolded shear strength (after Leroueil et al. CGJ. 1983)

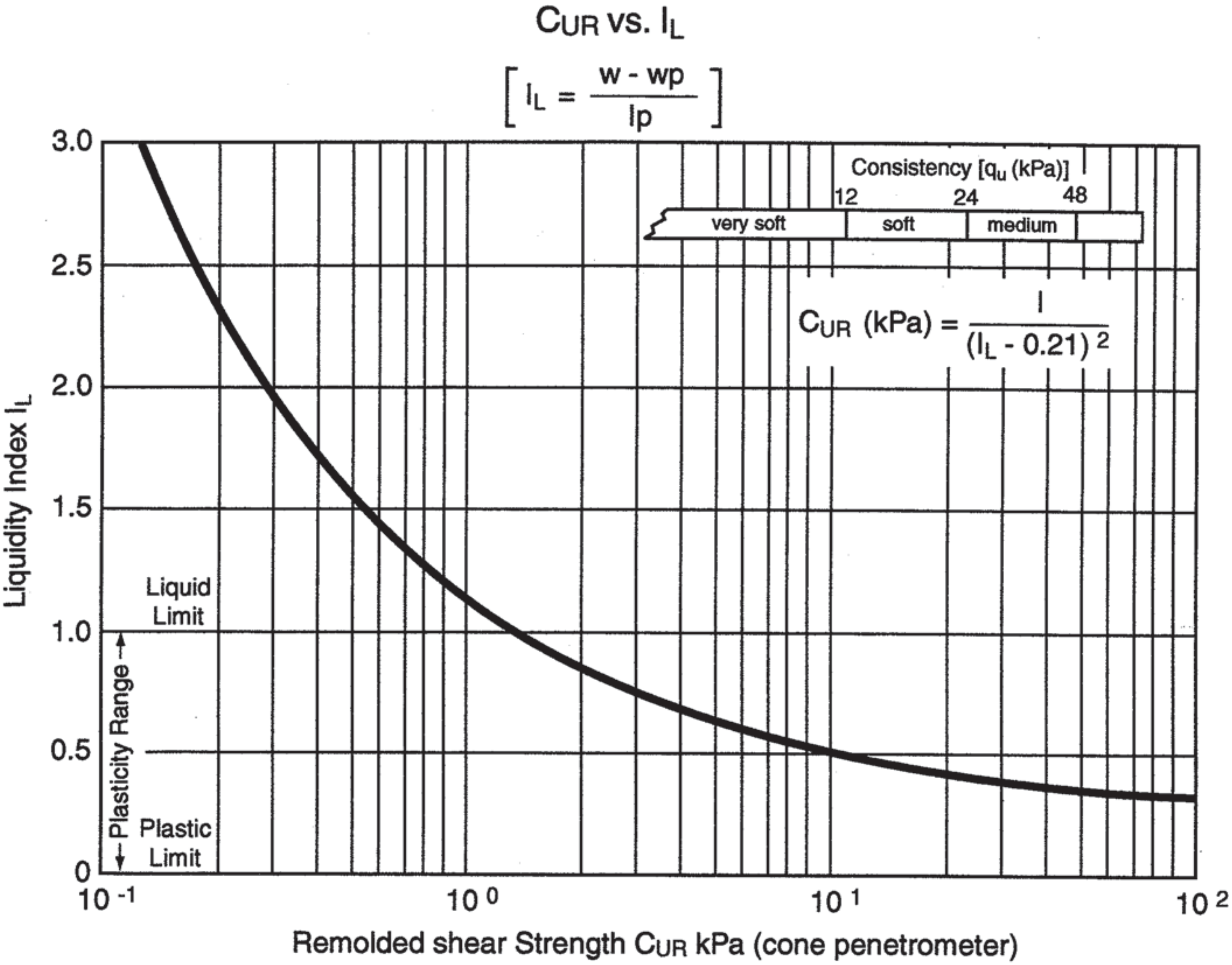


Fig. 22 Relationship between liquidity index and remolded shear strength (after Leroueil et al. CGJ. 1983)

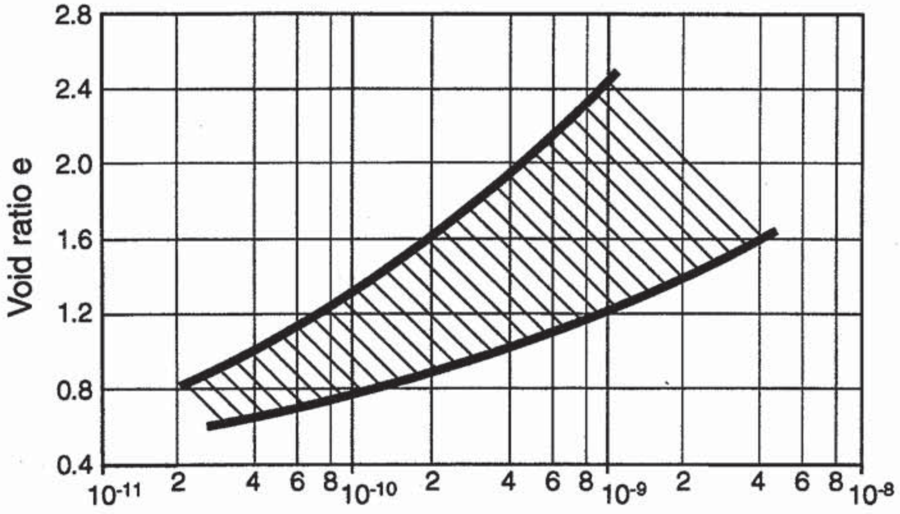


Fig. 23 Range of e vs. lg. k_v for Champlain Sea clays (after Travenas et al. 1983)

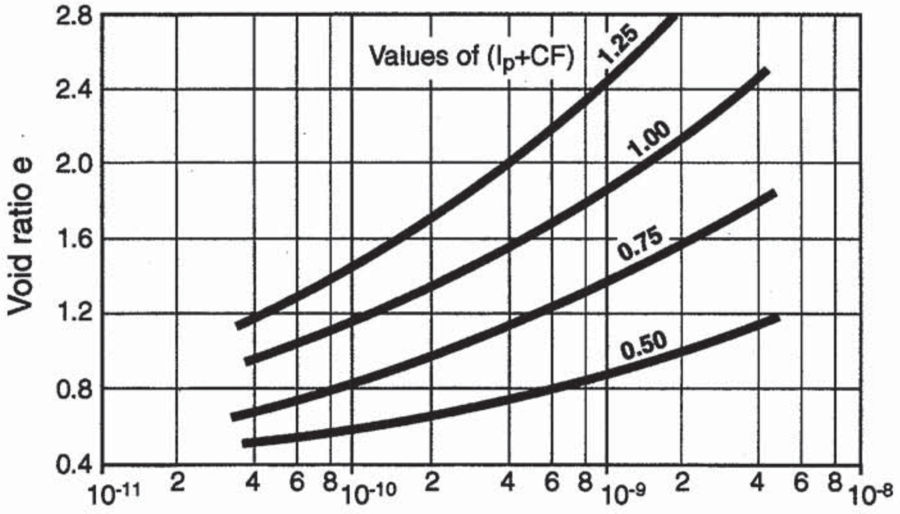
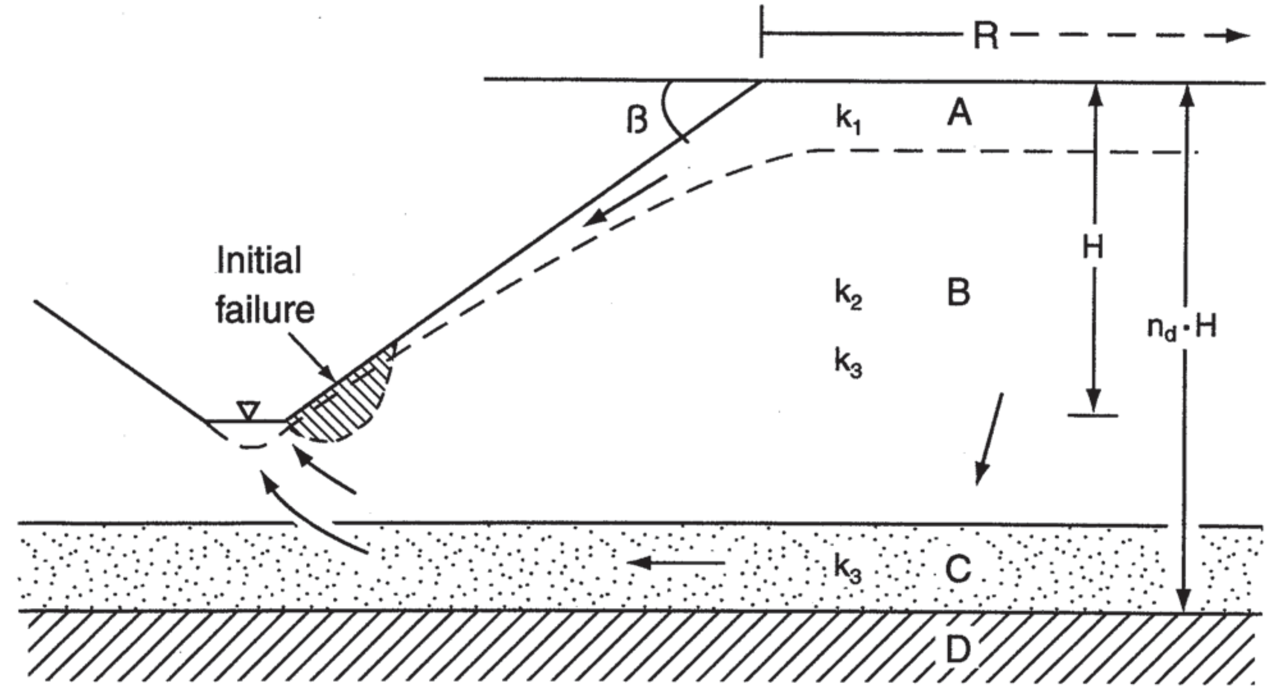


Fig. 24 Range of e vs. lg. k_v for Champlain Sea clays as a function of the empirical parameter (I_p + CF) (after Travenas et al. 1983)



A. Surficial layer of fissured clay and/or sand. $k_1 = 10_2\text{-}10_3\ k_2$; c_u range 10-100 kPa, avg. ≈ 80kPa.

B. Massive - stratified soft clay. $K_2 \approx 10^{-8}$ cm/s; at 3m depth c_u range 10-100 kPa, avg. 55 kPa; at 20m depth c_u range 40-120 kPa, avg. ≈ 80 kPa. rate of increase with depth approximate 2 kPa/m.

C. Drainage layer. $k_3 = 10\text{-}10^2\ k_2$.

D. Firm base comprising till and/or bedrock (essentially impermeable).

ß Slope angle.

H. Slope height.

n_d Depth factor (depth to a firm base as a multiple of slope height).

R. Distance of flow slide regression.

← Direction of groundwater flow.

Fig 25 Slope elements (permeability data from Lafleur and Lefebvre, 1980; c_u data from McLellan, 1979)

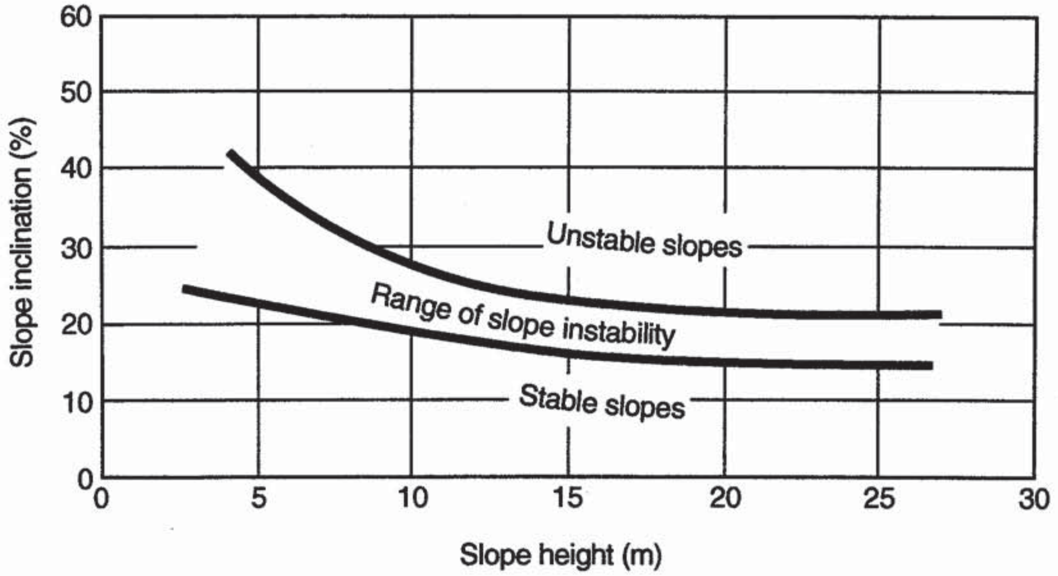


Fig. 26 Height - inclination relationships for unstable slopes in eastern Canada. (after Tavenas, 1984)

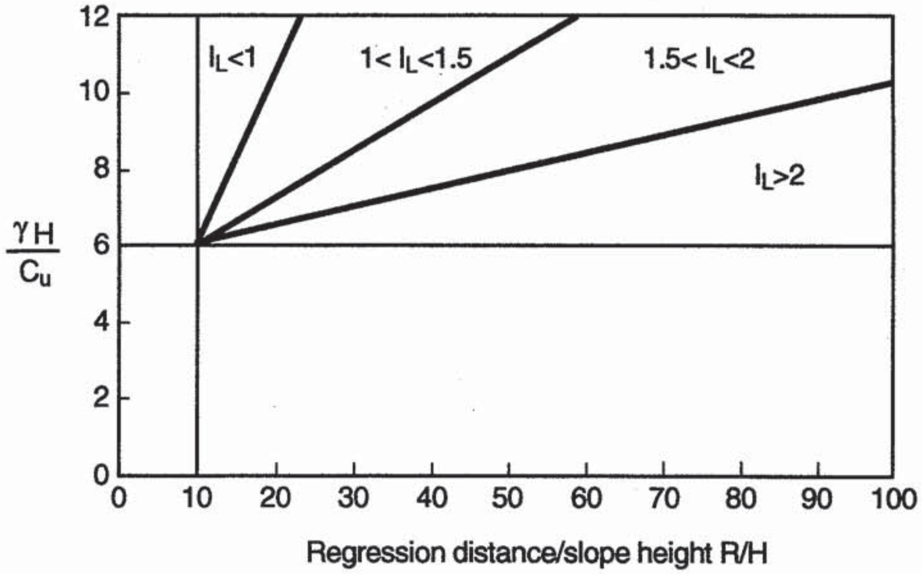


Fig. 27 Retrogression prediction method (after Mitchell and Markell, 1974)

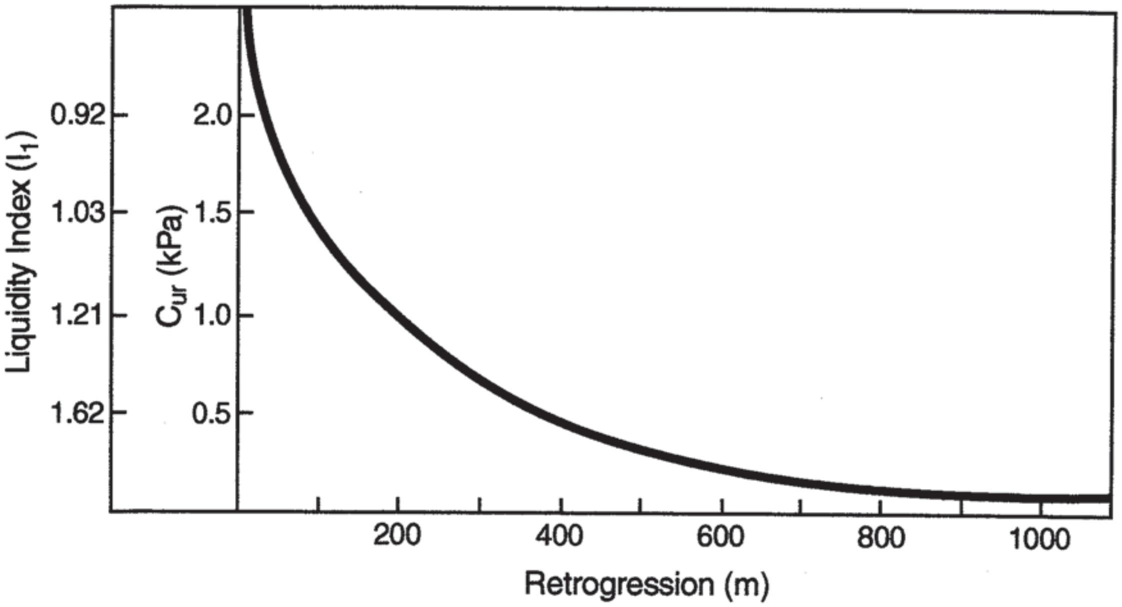


Fig.28 c_{ur} and I_L vs. distance of regression of earthflows. (after Lebuis et al. 1983)
(I_L vs. c_{ur} calculated from relationship given by Leroueil et al. 1983)