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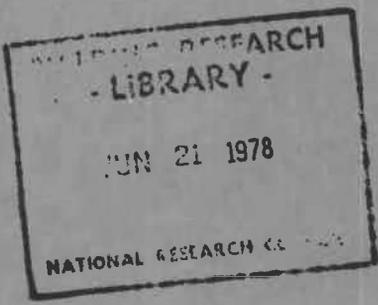
REVIEW OF ENGINEERING BEHAVIOUR OF MARINE CLAYS IN EASTERN CANADA

by E. Penner and K. N. Burn

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Review of engineering behaviour of marine clays in Eastern Canada

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Leda clay deposits are thought to belong to a single marine episode that sedimented in the Champlain Sea between 12 000 and 9000 years BP. Differential uplift ended the marine episode and subsequent sediments were deposited in estuarine followed by near-freshwater to lacustrine conditions. Rock-forming minerals consisting of feldspars, quartz and amphiboles make up a large part of the clay size fraction. The dominating phyllosilicates are micas and illites, or hydrous micas. The fabric of the deposit consists of an assemblage of silt and clay size rock fragments in which clay minerals are generally randomly oriented.

Major engineering problems are reviewed against the background of depositional history, nature of the soil fabric formed during sedimentation, subsequent structural alterations, mineral composition and pore water chemistry, all among the more important factors responsible for the engineering behaviour of these soils.

L'on croit généralement que les argiles Léda appartiennent à une seule épisode marine au cours de laquelle elles se seraient déposées dans la mer Champlain entre 12 000 et 9000 années avant notre siècle. Un soulèvement tectonique différentiel mit fin à l'épisode marine et les sédiments subséquents furent déposés dans des conditions d'estuaire suivies de conditions saumâtres et lacustres. Une bonne partie de la fraction de dimension argileuse est formée de minéraux constituant la roche-mère, soit du feldspar, du quartz et des amphiboles. Les phyllosilicates sont des micas et des illites, ou micas hydratés. La fabrique du dépôt consiste en un assemblage de fragments de roche de grosseur argileuse et silteuse dans lequel les minéraux argileux sont orientés de façon aléatoire.

Les principaux problèmes d'ingénieurs sont passés en revue en relation avec l'histoire de la déposition, la nature de la fabrique de sol formée durant la sédimentation, les altérations structurales subséquentes, la composition minérale et la composition chimique de l'eau interstitielle, tous parmi les facteurs les plus importants qui sont responsables du comportement des sols dans les problèmes d'ingénieurs.

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[Traduit par la revue]

The marine clays in the lowlands of the St. Lawrence River and its tributaries have unusual soil engineering characteristics closely related to their geological origin and to alterations that have occurred in their properties subsequent to deposition. Despite the engineering problems associated with these lowland soils, proximity to navigable waters, moderate climatic conditions, and closeness to Canadian and American markets have been overriding factors in the economic development of the region. It is now one of the more densely populated and heavily industrialized areas of the nation, a pattern that will continue to intensify in the foreseeable future.

Because of intensive research, the engineering experience already gained and the information available about similar soils, particularly those in Sweden and Norway, a good soil engineering design capability now exists in Canada. Failures, sometimes catastrophic (as with landslides), involving loss of both life and property, are not unknown, however, and these point to the need for a more complete understanding of the en-

gineering properties of marine clays. It is well known that the unusual behaviour of such soils can be attributed mainly to their geology, mineralogy, depositional environment, structure and, possibly, to alterations that have taken place subsequent to deposition. No attempt will be made to cover all the research contributions available, but this paper will highlight those studies that illustrate the problems on the one hand and, on the other, the features that have led or may lead in the future to substantial improvements in design and construction. Crawford (1968) surveyed earlier engineering studies; the emphasis in this paper will be placed on more recent developments.

Geology

The marine sediments were formed in the Champlain Sea during a single marine episode "that ended as a result of differential uplift of the land and was replaced in progressive stages first by estuarine then by freshwater lacustrine and fluvial ancestors of the present freshwater drainage system" (Gadd 1963). The fine sediments are by

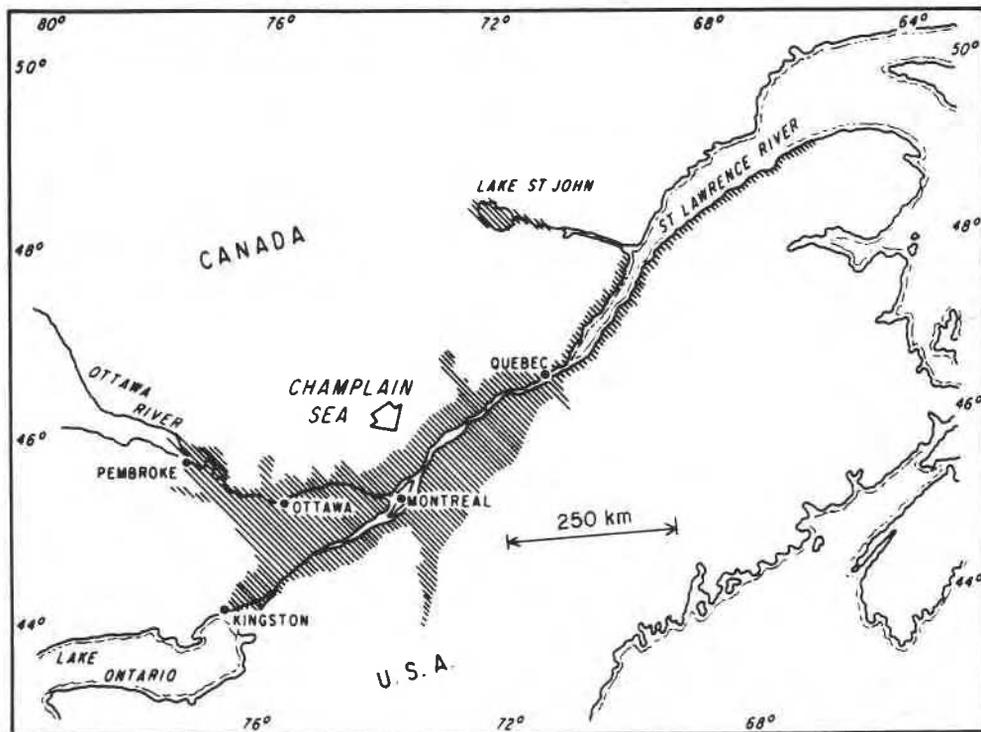


FIG. 1. The Champlain Sea (from Crawford (1968), reproduced with permission from Engineering Geology).

common usage referred to as Leda clay, although sometimes they consist almost completely of silt size particles or the proportion of silt is too large to be referred to as a clay.

These marine sediments are widespread throughout the Ottawa and St. Lawrence river valleys, reaching westward to the lower regions of Lake Ontario and extending northward into the Lake St. John drainage basin in the province of Quebec (Fig. 1). The deposits range from 10.7 to more than 61 m (35 to 200 ft) thick; dating studies place their time of origin between 12 000 and 9000 years BP, based on ^{14}C from shell and peat sources (Karrow 1961).

Mineralogy

The mineralogical composition of the marine clays may be summarized as follows (Brydon and Patry 1961; Gillott 1970): Montmorillonite or other expanding layer silicates are absent, or present only in small quantities. Some chlorites and vermiculites are normally present. Mica, hydrous mica, or illite are the predominant clay minerals. Rock-forming minerals in varying proportions of feldspars, quartz and amphibole make up a large part of the clay size fraction, with feldspars predominating. The same rock-forming

minerals found in the clay fraction are represented in the silt and sand size fractions. The major change accompanying particle size is an increase of phyllosilicates in the small-size fractions, with consequent dilution of the other minerals.

Several mineralogists have drawn attention to the existence of unstable primary minerals in the clay fractions signifying a youthful deposit. The minerals are almost certainly detrital, although chemical weathering or diagenesis may have contributed to the formation of some of the mixed-layer and expanding-lattice clay minerals (Gillott 1970).

Fabric, Structure and Sensitivity

The fabric of Leda clay consists of an assemblage of silt, clay size rock fragments, and clay minerals in which the arrangement of clay platelets ranges from a completely random orientation (card house fabric) to a preferred orientation where the flat platelets are parallel to the bedding plane. The more normal orientation of clay platelets existing in the field is somewhere between the two extremes.

Compressed anisotropically, the clay platelets tend to take on a preferred orientation normal to the direction of compression as the total void space is reduced. The change in fabric can be shown to

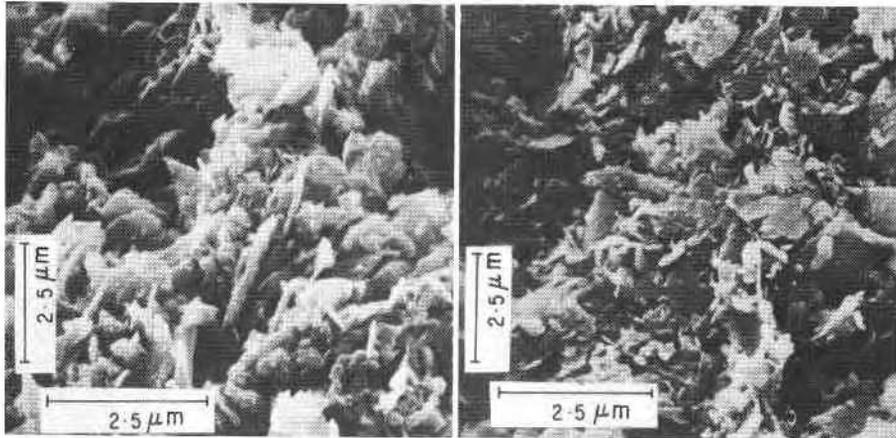


FIG. 2. Scanning electron micrographs of Leda clay from the Ottawa Sewage Plant from a depth of 16.2 m and a preconsolidation load of 478 kPa (from Gillott (1970), reproduced with permission from Engineering Geology).

be one of increasing, preferred particle alignment normal to the direction in which the load is applied. A preconsolidation load of 0.48 mPa was estimated for the sample shown in Fig. 2. The scanning electron micrograph of the sample shows some particle orientation parallel to the bedding plane. The degree of orientation was considerable, based on X-ray diffractograms using both chlorite and illite minerals (Gillott 1970). Penner (1963) also had studied preferred orientation in Leda clay, both by photographing the change in light reinforcement and interference during rotation of thin sections between crossed polaroids, and by anisotropic thermal conduction. Both methods gave the same results and were supported by Gillott's (1970) work.

The open type of fabric was formed during sedimentation in saline water of various levels of electrolyte concentration, i.e. marine or brackish water. It represents the type of fabric formed under conditions of flocculation where adjacent particles tend to aggregate during sedimentation because repulsion forces are low and they are brought into close proximity by their thermal energy. As the cations are partly polarized van der Waals forces of attraction take over. Subsequent consolidation by the physical weight of the sediment above brings the points of contact and the particles generally into still closer proximity.

The clay fabric develops structural strength in this way because of the forces of attraction and weight of the deposit above. In some cases it is said that the strength has been augmented further by the deposition of cementing materials such as iron oxides or carbonates around the points of

contact between particles. Bjerrum (1973) has indicated that cementing is not confined to the points of contact alone but is smeared over the entire surface of the particle.

All conditions required to produce a soil of high sensitivity¹ are now present. The forces of repulsion increase between particles when the electrolyte concentration is reduced in the pore water. This might occur during leaching of the clay with fresh water. Although the fabric remains intact, the structural resistance to stress and deformation is greatly diminished. Any physical disturbance of the structure causes the water to be released from the pores of the open fabric as contacts or bonds are broken down and the entire mass may become a viscous fluid.

This description, somewhat oversimplified here, is known as the leaching theory (Rosenqvist 1953). It is, however, only one means by which sensitivity may develop. Soderbloom (1960) performed experiments that led him to believe that oxidation plus infiltration of organic dispersing agents from peat beds might well account for increased sensitivity. Some freshwater deposits are also known to be quite sensitive.

Skempton and Northey (1952) have proposed a sensitivity classification that was modified subsequently by Rosenqvist (1955) (see Table 1). The measured sensitivity, however, may depend on the equipment or apparatus used and on test procedure (see, for example, Eden and Kubota (1961)). There are, therefore, two features that characterize the unusual behaviour of Leda clay as it is found

¹Sensitivity is the ratio of natural strength to remoulded strength.

TABLE 1. Classification of sensitivity

Range	Description
1	Insensitive
1-2	Clays of low sensitivity
2-4	Clays of medium sensitivity
4-8	Sensitive clays
8-16	Slightly quick clays
16-32	Medium quick clays
32-64	Very quick clays
> 64	Extra quick clays

today: (1) the possibility of excessively large settlements arising out of the open nature of the fabric, and (2) the possibility of a substantial loss of strength that cannot be recovered through thixotropic processes resulting from the breakdown of the structure.

Sensitivity and Electrokinetic Phenomena

Early work (Bjerrum 1954) on Norwegian marine clays showed a distinct inverse relation between clay sensitivity and the electrolyte content of pore water, which contrasts sharply with that of Leda clay. Figure 3 gives a plot of laboratory-measured sensitivity as a function of specific conductivity of pore water (Penner 1965). Table 2 gives the relation between the electrokinetic potential E_k , a measure of interparticle repulsion, and sensitivity. Soils with a low surface area (silty) tend, however, to be more sensitive for the same electrokinetic potential than soils with a moderately high surface area. It is clear that the degree of sensitivity of a soil is not uniquely dependent on any one factor; indeed sensitivity is an expression of many interrelated soil properties and the interplay of environmental factors. The electrokinetic potential, like sensitivity, is an expression of the present condition of the surface forces and becomes a powerful tool in studying the influence of various factors, e.g. salt content of the pore water.

One significant factor that emerges is the influence of mono and divalent cations on sensitivity. Table 2 shows that increases in the percentage of monovalent cations over divalent cations in the pore water varies directly with increases in sensitivity. An approximate value for salt concentration (g/L) in the pore water may be calculated by dividing the specific conductivity by the factor 1.52×10^{-3} .

Major Engineering Problems

There is currently a resurgence of research activity and renewed interest in the more important soil engineering problems in Leda clays. Increased

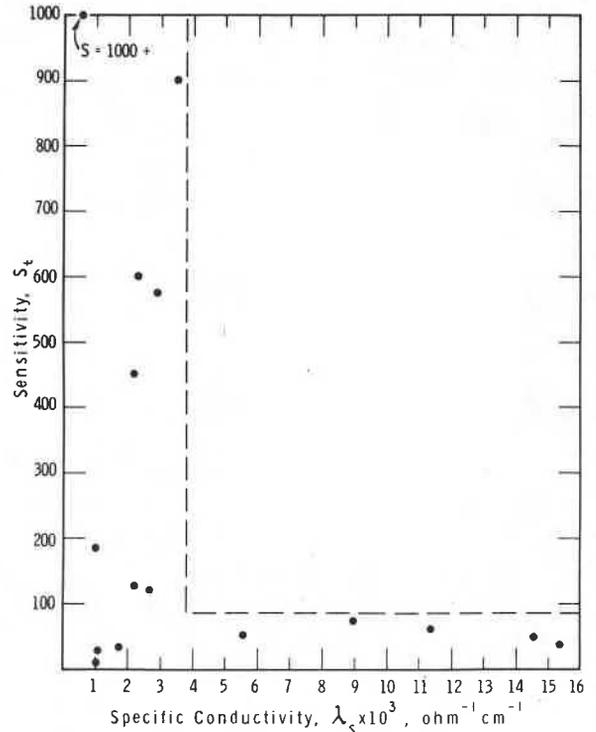


FIG. 3. Salt concentration of the pore water in terms of specific conductivity as a function of sensitivity (from Penner (1965), reproduced with permission from Canadian Journal of Earth Sciences).

construction activity has afforded greater opportunity to carry out field and laboratory research, and such studies have been supported generously by government grants to universities and industry. Attention is drawn mainly to the more recent and significant study areas illustrating the problems the authors consider to be of paramount importance. Much significant work, however, is still under way and is not available in the open literature for review.

Slope Stability and Flow Slides

It is highly significant that the sensitivity of Leda clay below the fissured drying crust is rarely less than 10 and sometimes reaches several thousand. The strength of the remoulded material at high sensitivities is often so low that measurements are not very precise. It is not surprising, therefore, that this vast deposit is scarred by characteristic flow slide features similar to those of the Scandinavian countries. Many flow slides occur each year, often with disastrous results. Examples of both old and new slides that took place on opposite sides of the South Nation River in Ontario are shown in Fig. 4, one only 2 years ago, the other, about 65 years ago (Eden *et al.* 1971).

TABLE 2. Electrokinetic potentials for soils listed in order of sensitivity*

Soil code No.†	Depth (m)	PI	E_k (mV)	S	MC (%)	Clay (%)	Surface area (m ² /g)	Specific cond. λ ($\times 10^3$)	Ca ⁺⁺ + Mg ⁺⁺ (%)	Na ⁺ + K ⁺ (%)
136-2	9.8	44	12.6	11	75.3	85	77.8	1	—	—
94-13-3	6.7	38	16.2	30	66.9	82	72	1.07	47	53
124-19-5	18.3	17	20.2	33	62.9	77	62	1.78	13	87
126-5-4	22.9	45	16.1	34	62.4	85	72	15.4	11	89
126-4-4	19.8	45	16.4	45	65.3	89	—	14.6	10	90
126-1-4	10.7	40	19.3	53	66.1	78	60	5.61	9	91
126-3-4	16.8	46	17.4	60	63.9	79	66	11.4	10	90
126-2-4	13.7	38	21.0	74	63.8	78	60	8.97	9	91
129-16-4	17.4	—	22.2	118	80.1	85	85	2.71	—	—
124-3-5	3.7	28	24.9	126	86.6	71	79	2.25	7	93
129-7-5	9.1	32	19.9	183	89.7	79	76	1.02	8	92
124-12-5	11.9	27	28.8	453	83.5	76	79	2.19	5	95
94-20-5	16.2	8	23.5	575	52.5	72	47	2.94	8	92
124-9-6	9.1	24	29.7	600	94.0	86	80	2.33	5	95
94-27-1	22.0	10	21.4	900	50.6	67	54	3.54	6	94
123-2-3	—	5	33.8	>1000	41.0	54	29	0.6	2	98

*From Penner (1965), reproduced with permission from Canadian Journal of Earth Sciences.

†Locations: 94, sewer plant; 123, Toulmoustou; 124, Gloucester; 126, Queensway Overpass; 129, Breckenridge, P.Q.; 136, Interceptor shaft.

A typical flow slide may be readily identified by its characteristic features. Figure 5 is a schematic drawing showing a section and perspective taken from a recent paper by Mitchell and Markell (1974). The most characteristic features are the overspill apron, normally consisting of liquefied soil, lumps of unremoulded surface material and other vegetative debris, the shape of the crater, and the spoil ridges and pinnacles if not destroyed or removed by erosion. Figure 4 does not show the apron because the spoil flowed into the river. When flow slides occur on river terraces not inundated in water, however, the apron is plainly evident and appears as a tongue of largely remoulded soil rivalling and sometimes exceeding in area the extent of the crater (Crawford 1961).

Features of old flow slides are easily identified on air photos. There are literally thousands of small flow slide scars throughout the marine clay region, along terraces, small creeks and streams and the banks of major rivers. A study by Mitchell and Markell (1974) showed that hundreds of flow slides of over 1 ha in area have occurred throughout Champlain Sea deposits in the provinces of Ontario and Quebec. Fifty of the larger ones were responsible for a total loss of life of over 100; and 40 000 ha of upland were destroyed in the process.

Two recent papers account for some improvement in the understanding of the flow slide mechanism. The mode of failure from laboratory studies of drained shear strength under low effective normal stress has resulted in a new appreciation of soil behaviour in the stress range that

applies to the stability of slopes (Eden and Mitchell 1970). It is possible, using information obtained in the course of a normal site investigation, to evaluate the susceptibility of a given site to slope failure and make a reasonable prediction of the extent of a potential earth flow according to Mitchell and Markell (1974).

In the latter study, slope profiles were established adjacent to identified landslides, using topographic maps, a stereo plotter and, in some cases, field surveys. In this way the value for H , the height of the slope, was obtained. To gather information on soil profile, soil classification and strength data from site investigation were used wherever available. Most of the values for undrained strength C_u and sensitivity were from field vane measurements, but where such information was not available soil sampling and field vane tests were carried out. Mitchell and Markell (1974) showed, for some 40 slides, that $\gamma H \cong C_u$ where γ is the bulk density (H and C_u are defined above). They showed, further, that the amount by which γH exceeded $6C_u$ correlated with the distance of retrogression, i.e. the distance from the mouth of the crater to the backscarp (Fig. 5). It appears therefore that a method is at hand for evaluating the potential danger associated with acres of flow slides and for measuring their magnitude.

The recent contribution of Eden and Mitchell (1970) involved determination of strength parameters under low effective normal stresses. Under these conditions the clay exhibited dilatant behaviour and a predominantly frictional shearing resistance. Dilatant behaviour was attributed to



FIG. 4. Flow slides on the South Nation River, Ontario (RCAF air photo).

the development of discontinuities on pre-existing planes of weakness and resulted in shearing of the clay into small blocks from 1 to 10 mm across. The frictional strength parameters were supported by field observations of the failure surface and the critical role of groundwater in slope instabilities. It was further shown that many slip surfaces develop simultaneously, so that an extensive zone of soil is considered to deform at the time of failure.

Shrinkage and Damage to Buildings

The collapse of the flocculated, open fabric that characterizes Leda clay, together with its very low content of swelling clay minerals, means that shrinkage is essentially irreversible. Differential shrinkage, either as the result of soil variability or the removal of water from one side of the foundation, can induce serious racking in both the foundation and the superstructure. Trees are a primary cause of shrinkage, occurring most notably in unusually dry summers. Shallow foundations used to support small structures and domestic dwellings are most often affected.

Figure 6 shows the ground movements induced by water removal by a row of elm trees. The deformations indicate the distance by which founda-

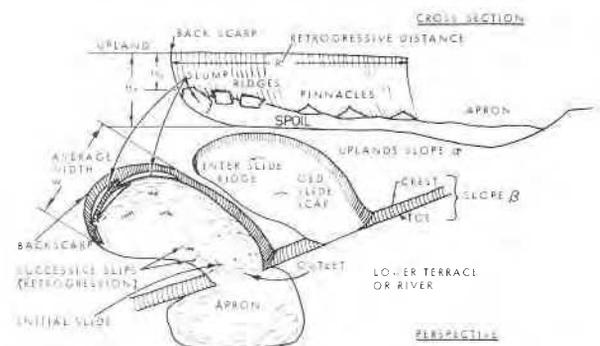


FIG. 5. Typical features of earthflows (from Mitchell and Markell (1974), reproduced with permission from Canadian Geotechnical Journal).

tions and trees should be separated if damage is to be avoided on this type of soil. Most of the trouble occurs during unusually dry seasons. When rainfall is low in summer the trees reduce the moisture content of the surrounding soil, inducing serious shrinking problems. Supplementing low rainfall by watering is not effective normally because it is impractical to supply water in sufficient quantities. Small trees or those that do not transpire excessively should be selected for new plantings. Heavy transpiration rates usually associated with

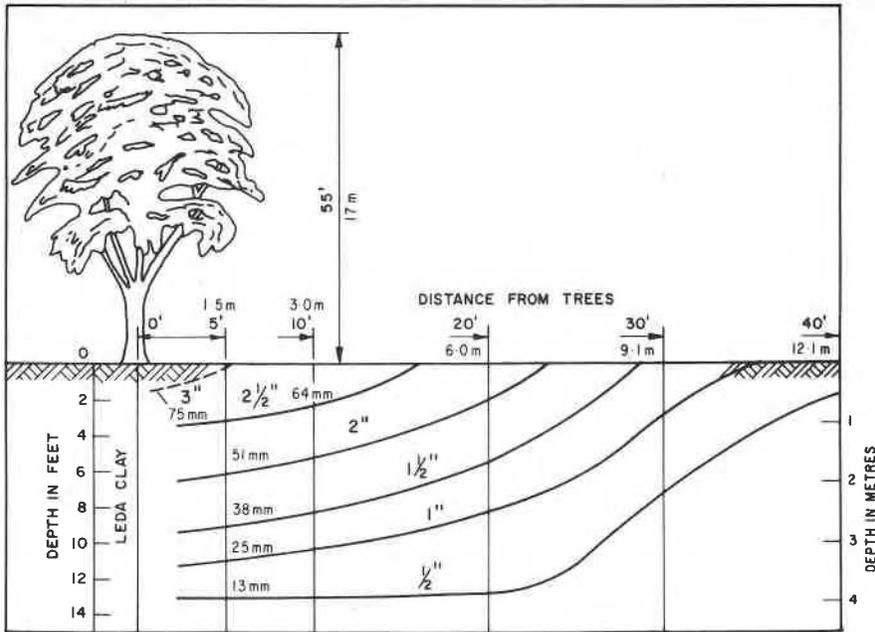


FIG. 6. Variation in maximum vertical ground movements in Leda clay near elm trees in 1955 (from Bozozuk (1962), reproduced with permission from Engineering Journal).

fast growing trees such as Lombardy poplars are to be avoided.

Studies carried out by Bozozuk (1962) in an area covering 36 city blocks in central Ottawa show the extent of existing damage and how it was specifically related to the proximity of trees to domestic dwellings. Recommendations now used for the prevention of such damage to shallow-founded structures by shrinkage in Leda clay from water removal by tree roots is based on extensive work carried out by Bozozuk and Burn (1960) and Bozozuk (1962). The more fundamental aspect of shrinkage and rewetting characteristics is described by Warkentin and Bozozuk (1961); and Burn (1973) has shown the rapidity with which shrinking is induced and the fact that severe damage is not confined to old houses.

Frost Heave and Uplift by Adfreezing

The relatively high water content of Leda clay, its high permeability and silty nature make these soils highly susceptible to frost heaving. The high permeability of the surface soil is related to its fissured nature. Water for frost heaving is readily available because a high water table exists at the beginning of most winters.

During an average winter in the Ottawa region the frost heave in snow-cleared areas is from 75

to 100 mm, attributable mainly to ice lens formation at the freezing front. Major highways are designed to avoid the heaving problem, but where design techniques have proved inadequate artificial insulation may be used (Penner 1966, 1968). On secondary roads differential heaving seriously reduces the riding quality and loss of subgrade strength results in rutting when the ice melts unless traffic restrictions are imposed.

The heaving pressure generated when displacement is resisted can be very high. Figure 7 gives the force developed over one winter period on a 305 mm diameter plate placed on the ground surface. Measurements of force between a rigid reaction frame anchored to rock and the surface plate show a force of 133 kN at the peak of the heaving season (Penner 1970a).

Foundation walls to which soil is allowed to freeze, as often happens in unheated buildings, can be displaced vertically (or in the direction of heat flow) by heaving forces as ice lenses develop. Such movements result when displacement due to ice lens growth in the soil is transmitted to the foundation wall by adfreezing forces; displacement may be even more serious if the frost line is allowed to penetrate below the footings of the foundation. This, however, is normally avoided by placing the footing below maximum frost depth. Displacement by adfreezing must be prevented by

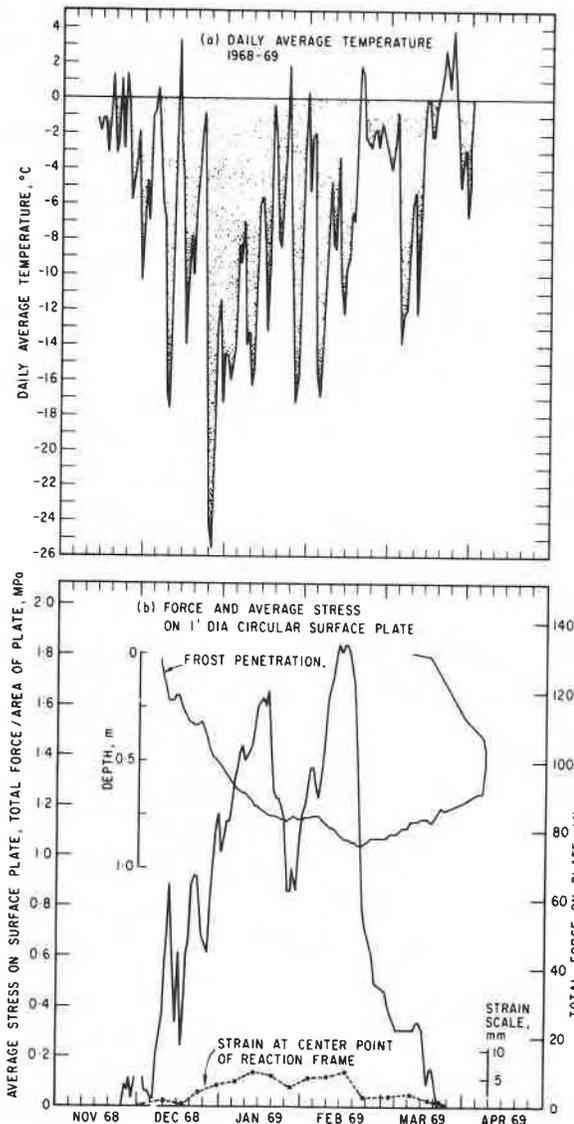


FIG. 7. Temperature, force and frost depth results on Leda clay (from Penner (1970a), reproduced with permission from Canadian Geotechnical Journal).

suitable design measures, including backfilling with nonfrost-susceptible material and drainage.

Figure 8 gives the force, adfreeze strength (Penner 1974) and small strain involved because of stiffness in the reaction frame. Such forces can be avoided by proper design, based on preventing adfreezing by the use of insulation or by replacing frost-susceptible soil with non-frost-heaving granular materials. For heated buildings the basement space temperature is normally sufficiently high to prevent adfreezing of the soil to the foundation wall. Backfilling around the foundation with gravel is also effective; this combined with good drainage

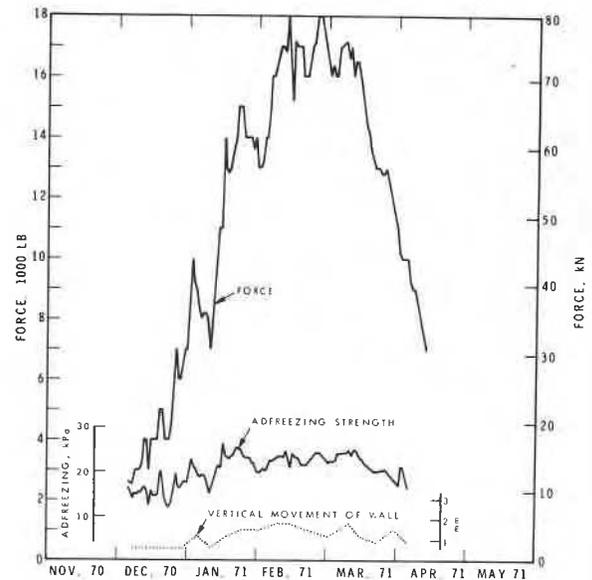


FIG. 8. Force measurements, calculated adfreeze strengths and vertical movement of block wall during heating period 1970-1971 (from Penner (1974), reproduced with permission from Canadian Geotechnical Journal).

at the footing level prevents any problem involving freezing even if the inside of the foundation walls are heavily insulated for reasons of heat conservation.

Thermal Conductivity of Leda Clay

Study of engineering problems that can arise when subgrade soils freeze below roads, streets and around the foundations of structures has led to the development of numerical methods for predicting heat flow and depth of frost penetration. To carry out such predictions, values for thermal conductivity of the soil are required and this has led to the development of techniques to measure this parameter. A laboratory method that appears reasonably satisfactory is based on transient heat flow, using a line heat source. In recent thermal conductivity studies of Leda clay (Penner 1970b) a 229 mm long, 0.5 mm diameter steel probe was used. From the phase composition given in Fig. 9 and the results of measurements using this apparatus, values of thermal conductivity were determined as given in Fig. 10. The thermal conductivity of frozen Leda clay rises rapidly as the freezing temperature is lowered because the thermal conductivity of ice is about four times that of water. Because Leda clays in the field have high moisture contents this factor becomes very important in carrying out heat flow calculations involving temperatures below 0°C.

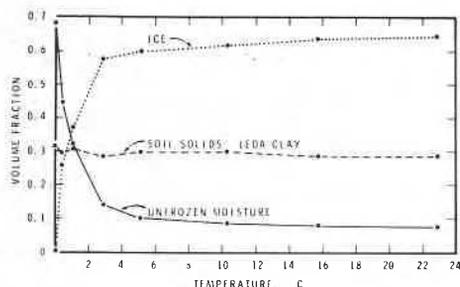


FIG. 9. Phase composition as a function of temperature for undisturbed Leda clay samples (from Penner (1970b), reproduced with permission from Canadian Journal of Earth Sciences).

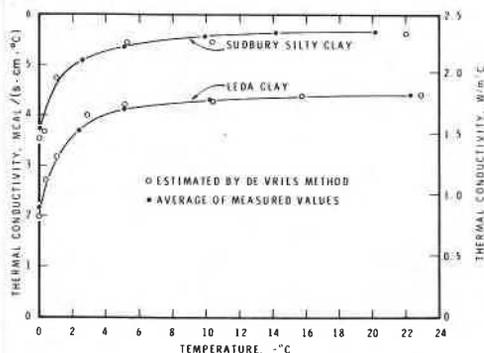


FIG. 10. Estimated and measured thermal conductivity of partially frozen soil (from Penner (1970b), reproduced with permission from Canadian Journal of Earth Sciences).

Undisturbed Field Sampling and Storage

A basic premise underlying laboratory testing of soil is that the condition of the sample in the laboratory can be made to simulate the field condition, so that in all respects its behaviour will represent that of in-place soil. At present there is no way in which soils can be sampled and placed in a testing apparatus without some change or disturbance occurring because of stress release and handling. Sensitive clays such as Leda clay are particularly susceptible to sample disturbance owing to the very nature of the soil fabric. There is, of course, quite a range of strengths within the Champlain Sea deposit, depending on location and depth. The 'brittle' deposits usually have a very high sensitivity and are thought to be most easily disturbed during the sampling process. They are normally considered to have 'cemented bonds', although the existence of cementation has not been shown except by indirect evidence. Soil samplers disturb the soil primarily because an extra volume of material, usually in the form of a thin-walled sampling tube, is introduced into the soil in retrieving the sample. Depending on the design of the sampler the disturbance will vary, the least

occurring when it is possible to trim sample blocks of soil from the bottom of an excavation.

An opportunity to compare the results from test specimens obtained with a number of different samplers and from block samples arose during excavation to 21.3 m for pump wells at a sewage treatment plant near Ottawa. Shear strengths were also compared with those obtained with a field vane apparatus (Eden 1971).

Details of the four types of tube sampler may be found in the literature. All are standard samplers used in marine clays in Canada and Scandinavia. The plotted results (Fig. 11) of preconsolidation pressure and undrained shear strength show the poor relative quality of samples taken with tubes compared with block samples. The author states that only four of the 35 preconsolidation test results were equal to or greater than those from the blocks; only 6 of 240 undrained strength tests were equal to or greater than the block tests. The laboratory test results indicated that values obtained from tube samples were only half as large as those obtained from samples taken from hand-trimmed blocks. Similarly, undrained shear strengths from the field vane over the entire depth were also lower. Eden (1971) concluded that "the sampling of sensitive clays can lead to extensive disturbance and must be considered seriously in any geotechnical investigation".

Comparisons have also been made by Bozozuk (1971) at a different site and on a softer Leda clay deposit to a depth of 6.1 m using samplers of two different sizes. He concluded that large-diameter tube samplers provide better quality samples than small ones, but there was no opportunity to compare tube sample results with those from large, hand-trimmed block samples because there was no deep excavation. Bozozuk (1971) also evaluated the effect of storage on the measured preconsolidation pressure of a block sample. He was able to show that after 17 months of storage in a constant-temperature (12.8°C), high relative humidity (90–100%) chamber, the measured preconsolidation pressure was reduced by 5%. He concluded that consolidation tests should be performed soon after sampling, although the decrease was not considered to be very important.

Settlement

The Geotechnical Section of the Division of Building Research, National Research Council of Canada, has, over the years, measured consolidation settlements resulting from various kinds of loads, including highway embankments for bridge

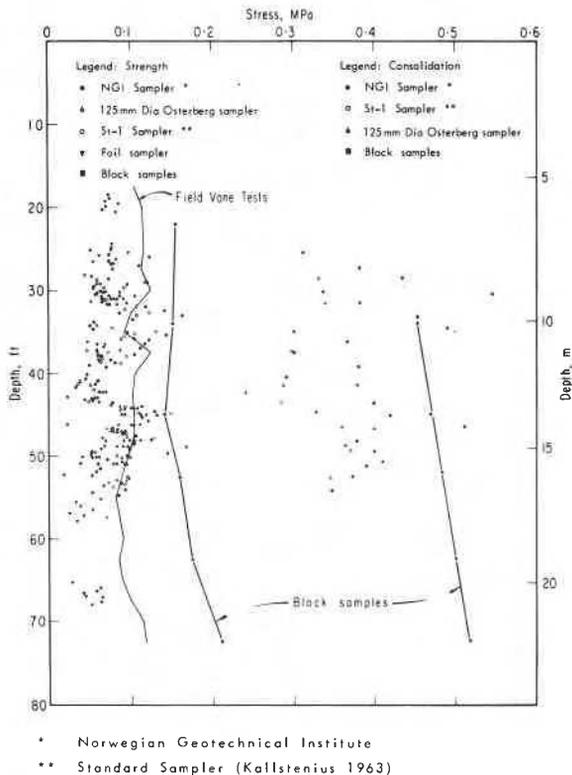


FIG. 11. Comparison of test results obtained on various sampler types (from Eden (1971), reproduced with permission from American Society for Testing and Materials).

approaches and mat foundations for apartment blocks. The predicted and, hence, the design settlements were based on laboratory testing, interpretation and stress analysis and have not been very accurate with respect to either rate of settlement or total settlement. Although predictions of total settlements have generally been better than those for rates, the fabric and structure of Leda clay imparts to the soil unusual compressibility characteristics. It has been shown repeatedly that the usual approach to field settlement predictions (from laboratory tests as a model of field behaviour and the classical theory of consolidation for the test interpretation) has severe limitations with this type of soil. Despite the disparities, laboratory consolidation determinations are still being used. The test procedure, including the rate of load application and interpretation of results, has been intensively investigated and there have been substantial improvements (Hamilton and Crawford 1959; Crawford 1964).

A major factor in the prediction of settlement hinges on an understanding of both types that occur. During 'primary consolidation', settlement

is controlled by the permeability of the soil and the escape of pore water under pressure. When the pore-water pressure gradient has dissipated, settlement continues at a much slower rate that is normally referred to as 'secondary consolidation'. The phenomenon of secondary consolidation in Leda clay also appears to occur below the preconsolidation stress when no primary consolidation is involved and in practice accounts for fairly large settlements. In recent years research activity has moved towards interpretation of the observed time-settlement behaviour in terms of other than classical concepts.

In a recent study of the records of settlement of a single-storey building Crawford and Burn (1976) showed that considerable settlement occurs under constant effective stress conditions in the vicinity of preconsolidation stress, although the total stress on the soil is somewhat higher. 'Primary' consolidation, in which pore-water pressures were high, was over in 2-3 years, but low excess pore-water pressures, attributed to the slow breakdown of the clay structure, continued at a rate balanced by drainage.

Earlier, Eden (1961) suggested a number of reasons for the disparity between measured settlement in the field and settlement predictions based on laboratory test and consolidation theory. The first, and a major factor, is the sensitivity of the clay structure to disturbance and the effects of sampling (Eden 1971). The second is that the shape of the laboratory load-deflection curve, which is typical of especially sensitive clays (Terzaghi and Peck 1948), makes it difficult to determine accurately either preconsolidation stress or appropriate parameters for the rate and magnitude of primary compression. The third is that highly compressible layers of Leda clay are frequently overlain by a stiff crust. This makes it difficult to assess the distribution and intensity of the stresses in the soft layers below.

Jarrett (1967) has pointed out also that the generally accepted Terzaghi theory assumes that the only retarding mechanism of compression is the dissipation of pore-water pressure and totally ignores the importance of structure-time effects. In reviewing the work of Crawford (1964, 1965) and the interpretation of the consolidation test, Jarrett suggested that in a slow laboratory test (although conducted at a rate about 2000 times faster than that in the field) much of the consolidation taking place might normally be classed as "secondary".

Eden and Poorooshasb (1968) and Jarrett (1967) agree that there are three phases in the

TABLE 3. Settlement of compressible layers after 15 years

Location (Ottawa area)	Soil depth (m)	Total settle- ment (cm)	Compressible layer			Average effective stresses in layer*				Stress ratios	
			Thick- ness (m)	Compres- sion		p_0	p_c	Δp	p_f	$\frac{\Delta p}{p_c - p_0}$	$\frac{p_f}{p_c}$
				(cm)	(cm)						
Apartment buildings	15	1.7	9.0	1.7	0.19	0.70	2.40	0.60	1.30	0.35	0.54
Green Creek	37	13.3	15.0	7.5	0.50	0.70	3.20	1.10	1.80	0.44	0.56
Main Street	27	16.2	7.3	7.7	1.06	0.50	2.70	1.22	1.72	0.55	0.64
Gloucester	20	27.4	3.7	21.9	6.00	0.43	0.62	0.32	0.75	1.68	1.20
Kars	15	64.0	6.0	40.1	6.70	0.65	1.40	1.50	2.15	2.00	1.54

*NOTE: p_0 = *in situ* effective stress; p_c = preconsolidation stress; Δp = stress increase due to applied load; p_f = *in situ* stress plus applied stress = final stress.

consolidation of Leda clay. Phase 1 is the elastic deformation range up to the preconsolidation pressure; phase 2 is a stage of fabric breakdown by a form of structural viscosity beyond the preconsolidation stress; and phase 3 is a classical process of primary consolidation with a definite relation between pressure and void ratio. Burn and Hamilton (1968), who studied loading of the soil below the preconsolidation stress, pointed out that structural breakdown in the clay also occurs where the soil is loaded below the preconsolidation stress. Settlements of significant magnitude continue long after loads are applied and therefore cannot be classified as 'elastic'.

Eden and Poorooshab (1968) suggested that the second phase accounts for a significant part of the settlement observed at one of the sites they studied, and for the uniform but low pore-water pressures persisting throughout the soft compressible layer.

A more cogent argument in support of the concept of continuing structural breakdown is that at one site where there was considerable increase in density following a 7% compression of the clay layer, no increase in shear strength could be detected with the field vane apparatus.

Load settlements in the field are complex and predictions are fraught with difficulties, primarily because of the sensitive nature of the clay soil and its slow structural breakdown when subjected to load increases. Significant settlements may occur when stress increases are either above or below the preconsolidation stress. Table 3 summarizes settlements of compressible layers at various sites after 15 years of observations. Stress ratios less than 1.00 indicate loads below the preconsolidation stress. (This information updates that given by Crawford (1968) after 7 years of observation.)

Although predictions of settlements where sensitive clay deposits are loaded are not as accurate

as may be desired, there has been considerable advance in the understanding of soil behaviour: improvements in techniques for sampling sensitive soils; improvements in laboratory testing procedures that better simulate field conditions; and better understanding of the structure of the clay and its time-dependent characteristics.

Pile Loads by Negative Skin Friction

Piles located in deposits subjected to settlement carry down-drag or negative skin friction loads. Again, this is particularly important in Leda clay because of its high compressibility. The designer needs to know the magnitude of such loads in addition to those imposed by the structure.

The performance of both the end-bearing piles (Bozozuk and Labrecque 1969) and the free-floating pile (Bozozuk 1972) has been described in detail. The instrumentation used to assess loading of piles by settlement was described earlier by Crawford (1969) and a useful resume of the field results was given by Bozozuk (1970).

End-bearing piles were installed to support an overpass structure of 4450 kN where the Leda clay deposit is some 82 m thick. The 48.8 m free-floating test pile was located on the centre line of a 9.1 m high bridge embankment. End-bearing composite piles 91.4 mm in diameter, 82.3 m long and of 12.7 mm wall thickness were filled with reinforced concrete and subjected to down-drag loads while the embankment included settlements in the clay. During the first 5 years the clay deposit settled 2.1 m, of which 0.46 m occurred after pile installation. In the first 3 years the negative skin friction load on each pile reached 7500 kN or 70% of the design value. During the same period the negative skin friction load on the floating steel tube pile, 305 mm in diameter and of 6.35 mm wall thickness, reached 1200 kN.

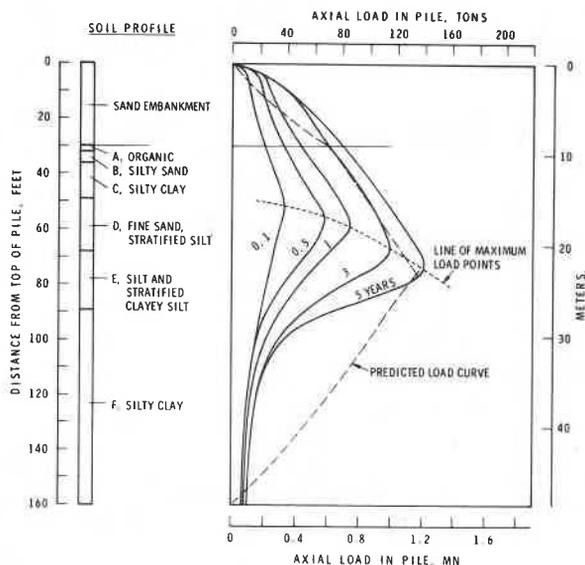


FIG. 12. Variation of skin friction load on 12-in. (305 mm) diameter steel pile with time (from Bozozuk (1972), reproduced with permission from Canadian Geotechnical Journal).

Bozozuk (1972) has shown that skin friction loads are related to horizontal effective stress acting on the skin. The predicted and observed loads on the free-floating pile compared favourably with respect to both neutral point and magnitude of load. Figure 12 gives comparisons at various times following pile installation.

Summary and Concluding Remarks

Geology, Mineralogy and Physico-chemical Behaviour

The Champlain Sea deposits are of post-glacial origin and cover extensive areas in the St. Lawrence and Ottawa river valleys, important for their heavy industrialization and dense population. That micas and illites are the predominant clay minerals has been verified. Feldspars, quartz and amphiboles in that quantitative order make up a large part of the clay size fraction.

The fabric of the deposit consists of a randomly oriented assemblage of clay minerals interspersed with 'rock flour'. A high moisture content is characteristic of this open geometric configuration, which reduces to a viscous slurry on collapse of the very sensitive materials. Major engineering problems such as flow slides and massive settlements, among others, are the direct consequence of an initially high moisture content that leads to structural collapse.

Sensitivity is a property closely identified with flocculated marine clays that have undergone

post-depositional leaching. It has been shown to correlate directly with measured electro-kinetic potential (E_k), but not with pore water salt content. Below approximately 3 g of salt per litre of pore water, sensitivity is variable but high; above this, it is constant and relatively low. The physical properties that account for the engineering behaviour of Leda clay generally parallel those of the Scandinavian marine clays.

The cause of brittleness is still controversial, although it is normally attributed to interparticle cementation. That, however, remains to be proved as far as Leda clays are concerned. In a general way the basis for the unusual behaviour of these sensitive clays is understood in physico-chemical terms, but solutions to engineering problems in Leda clay have not advanced as rapidly. Nonetheless, a good design capability now exists in Canada.

Major Engineering Problems

Flow slide scars are extensive along terraces, streams and riverbanks throughout the Leda clay deposit. More are added each year. Most recent studies indicate that hazardous slopes can be identified from the ratio of $\gamma H/C_u$, soil sensitivity, and ground and surface water conditions, particularly in the spring of the year. Warning systems are being studied as a temporary measure, but to protect both life and property stabilization techniques are needed. At present, both the identification of hazardous slopes and designs for their stabilization have not reached a satisfactory level, although work on these problems is continuing.

Damage to buildings from settlements around foundations can often be traced to the removal of water by trees. This type of damage is well understood and unnecessary settlements are accentuated during dry periods, but with proper landscaping techniques such problems can be avoided. Salient aspects of damage to foundations by trees include the following: (1) Consumption of water is proportional to the size of tree. (2) Fast-growing trees require copious amounts of water. (3) During landscaping it should be remembered that the distance between tree and building should be about the same as the height of the mature tree. (4) Rows of trees are especially aggressive with respect to water consumption and extend their influence further than individual trees. (5) As soon as settlement damage is observed any offending trees should be removed.

Leda clays are generally highly frost susceptible owing to their silty texture. In most regions the

water table rises to the surface prior to the onset of winter. The two damaging aspects of frost action are frost heaving and loss of strength when thawing occurs. Frost damage to roads is generally avoided by replacing frost susceptible materials with granular fill or preventing freezing by the use of thermal insulation. In heated structures frost damage is rarely a problem, but for unheated structures preventive measures are much the same as for roads. In general, attempts to resist frost heave forces by loading are not considered a viable engineering solution because of their magnitude. In the more heavily textured deposits uplift pressures of 1.9 MPa have been measured. When calculating thermal patterns under roads and around buildings it must be remembered that thermal conductivity of ice is four times greater than that of water. This is of particular significance in high water content deposits such as Leda clay.

It is believed that in tube sampling of brittle soils particularly, serious disturbance can occur as a result of lateral strain. Of necessity, samplers must have a clearance ratio to reduce friction when the sample moves inside the tube during the sampling process. Eden (1971) has concluded that "at the present time . . . large undisturbed block samples are the only ones that can be relied upon consistently". Comparison of laboratory tests of specimens from so-called 'undisturbed' tube samples and block samples indicate that the latter have twice the undrained strength. Sample disturbance has caused much concern, and greater emphasis has recently been placed on perfecting *in situ* measuring equipment and techniques. Sample storage has also been investigated, but with proper facilities (constant temperature T and high relative humidities) its influence has been shown to reduce the original measured values by only 5% after 17 months of storage.

With regard to settlement in Leda clay from various sources such as embankments, bridge approaches, mat foundations, etc., the structural breakdown of the soil has been observed in terms of the resulting compression. The actual mechanism of volume compliance on a microscopic scale and the roles played by permeability and pore pressures both below and above preconsolidation pressures are not well understood. Part of the difficulty of attempting to draw conclusions or derive empirical relations between observations of settlements and ratios of applied load to preconsolidation load lies with the limited accuracy with which preconsolidation pressure can be determined. It is unlikely that gains can be made in

this direction. If much improved methods of sampling are developed or more reliable results are obtained with *in situ* methods this could change. The time settlement relations of laboratory tests to actual field load conditions must, however, be better understood in a quantitative sense before predictions of settlement with time can be more realistic.

Skin friction loads on a floating test pile in marine clay have been shown to be related to the effective horizontal pressures acting on the pile. The predicted friction loads compared favourably with measured loads with respect to both location on the pile and magnitude.

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