The permeability of natural soft clays. Part II: Permeability characteristics

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The permeability characteristics of a number of intact natural soft clays from Québec, the USA, and Sweden have been investigated in the laboratory. The variation of permeability with void ratio is best represented in terms of a linear e vs. lg k relation which is generally valid in the range of volumetric strains encountered in engineering practice.

The permeability at the *in-situ* void ratio is shown to be a complex function of such parameters as the void ratio, the clay fraction, the plasticity index, and the fabric of the clay. Permeability anisotropy is negligible in marine clays.

The e vs. lg k relationships of the various clays tested are well ordered in terms of an empirical parameter (I_p + clay fraction), irrespective of the geological origin of the clay. The slope of the e vs. lg k relationship, referred to as permeability change index C_k, is simply related to the initial void ratio by $C_k = 0.5e_o$.

Keywords: permeability, clays, laboratory tests, permeability anisotropy, permeability – void ratio relations.

Les caractéristiques de perméabilité d'une série d'argiles molles naturelles intactes du Québec, des USA, et de Suède ont été étudiées au laboratoire. La variation de la perméabilité avec l'indice des vides est représentée au mieux par une relation linéaire e vs lg k qui est généralement valable dans le domaine de déformations volumétriques rencontré en pratique.

On montre que la perméabilité à l'indice des vides en place est une fonction complexe de paramètres tels que l'indice des vides, la fraction argileuse, l'indice de plasticité et la structure de l'argile. L'anisotropie de perméabilité est négligeable dans les argiles marines.

Les relations e vs lg k des différentes argiles étudiées sont bien classées en fonction du paramètre empirique (I_p + fraction argileuse), quelle que soit l'origine géologique de l'argile. La pente de la relation e vs lg k appelée indice de changement de perméabilité C_k est reliée de façon simple à l'indice des vides initial par $C_k = 0,5e_o$.

Mots-clés: perméabilité, argiles, essais de laboratoire, anisotropie de perméabilité, relations perméabilité – indice des vides.

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1. Introduction

Permeability is one of the fundamental properties of soils. It governs such important engineering problems as the groundwater regime in stratified deposits, or near natural and excavated slopes, the flow of water through or around engineered structures, the consolidation of clay foundations under applied loads, or, to some extent, the migration of pollutants from waste disposal facilities.

Numerous papers have been published in the past, dealing with such fundamental aspects of the permeability of soils as the validity of Darcy's law or the factors governing the magnitude of the coefficient of permeability k. However, the majority of past laboratory investigations was concerned with artificial or remolded soils, while the number of studies on the permeability of intact natural clays has been remarkably limited (Jacobson 1955; Raymond and Azzouz 1969; Casagrande and Poulos 1969; Abelev 1973; Amar and Dupuy 1973; Chan and Kenney 1973; Goodall and Quigley 1977).

In view of the importance of a reliable assessment of the permeability characteristics of natural clays for such problems as the analysis of consolidation (Mesri and Rokhsar 1974; Tavenas *et al.* 1979), the long term behaviour of man-made and natural slopes (Eigenbrod 1975; Kenney and Chan 1973; Kenney 1979), or the design of waste disposal facilities (Goodall and Quigley 1977), it seems necessary to develop a thorough investigation of these characteristics.

As part of continuing research on the properties of natural clays and on the behaviour of clay foundations, a comprehensive research program on the permeability of natural soft clays was developed at Laval University. After an investigation of the methods of measuring k in the laboratory, and of the validity of Darcy's law (Tavenas *et al.* 1983), a wide variety of intact soft clays from North America and Scandinavia have been tested to define such characteristics as the vertical permeability and the permeability anisotropy at the *in-situ* conditions as well as the variations of k during consolidation. The results of this study are presented herein. As a final stage of the research, the methods of measuring the permeability *in situ* are presently under investigation.

2. Objectives and method of investigation

The analysis of engineering problems involving the flow of pore water through clayey soils usually requires two types of permeability data: the magnitude and the anisotropy of k at the *in-situ* void ratio and structural conditions of the natural clay deposit, and the mode of variation of k when the clay is compressed under a structure. The objectives of the present investigation were to define the best method of describing the permeability behaviour of natural clays, to measure k at the *in-situ* conditions, to identify any effect of anisotropy at the *in-situ* conditions, and to define simple parameters for the variation of k during consolidation. By testing a number of soft clays from different geological origins and with a wide range of physical and mechanical properties, it was intended to obtain an insight into the factors governing the permeability of natural clays and possibly to develop empirical correlation between permeability characteristics and other clay properties. A total of 14 intact natural soft clays have been considered in the present investigation: 8 are Champlain sea clays from sites scattered between the Ontario–Québec limit and Saint-Alban in the Province of Québec, 2 are Tyrrell sea clays from the James Bay area in Québec, 1 is a lacustrine varved clay from northwest Québec, 1 is the Atchafalaya clay in the Mississippi Delta, and 2 are marine clays from the East and West coasts of Sweden.

2.1. Sampling

The quality of sampling is a key element in any laboratory investigation of the behaviour of natural clays. It has been recognized in the past that common, small diameter piston sampling techniques often adversely affect the structure and the behaviour of soft clay specimens (La Rochelle and Lefebvre 1971). New sampling methods have been developed to avoid this problem, and were used in the present research.

Of the 14 different clays investigated, 12 were sampled by means of a 200 mm diameter thin tube sampler with overcoring device developed at Laval University for the specific purpose of undisturbed sampling of soft sensitive clays: all Champlain sea clays, the Matagami varved clay, the Atchafalaya clay in the USA, and the Bäckebol and Lilla Mellösa clays in Sweden were all sampled using the equipment and technique described by La Rochelle *et al.* (1981). The Tyrrell sea clays at B2 and B6 were sampled using the equipment and method developed at the University of Sherbrooke (Lefebvre and Poulin 1979); the samples were taken by University of Sherbrooke personnel as part of a contract with the Société d'Energie de la Baie James. Past studies have shown that these two sampling methods produce intact specimens of a quality equivalent to block samples.

2.2. Testing methods

For most clays the testing program consisted first of a constant head permeability test in a large triaxial cell on a 200 mm diameter, 100 mm high specimen, consolidated to the *in-situ* effective stresses. Following this test the specimen was cut into a vertical and a horizontal 50 mm diameter, 50 mm high specimen for permeability tests in a triaxial cell as well as a vertical and a horizontal 50 mm diameter, 19 mm high oedometer specimen. The small triaxial specimens were tested in constant head tests at the *in-situ* stress conditions. The oedometer specimens were submitted to a conventional compression test, the permeability being measured by means of falling head tests at various stages of compression, so as to define the void ratio – permeability relationship. This combination of tests on large and small specimens in the vertical and horizontal direction was adopted so as to evaluate scale effects as well as the anisotropy of permeability.

The triaxial tests on both 200 mm and 50 mm diameter specimens were performed in specially designed "leak-free" cells as described by Tavenas *et al.* (1983). The specimens were mounted under water to ensure proper saturation and were confined in water saturated rubber membranes. Silicone oil was used as a cell fluid. All specimens were back pressured to 100 kPa. The vertical specimens were consolidated to the *in-situ* effective stress conditions assuming $K_o = 0.55$; in a few cases, for specimens at shallow depths, σ_{3c}' was selected in excess of σ_{ho}' so as to ensure a proper contact between the membrane and the periphery of the specimen. The horizontal specimens were isotropically consolidated to $p' = (\sigma_{vo}' + 2\sigma_{ho}')/3 = 0.7\sigma_{vo}'$. Constant head permeability tests were performed using distilled water as a permeant. Adverse effects of this type of permeant, as reported by Wilkinson (1969), have not been observed in the present study: constant values of k were observed once the effects of consolidation/swelling related to the application of the gradient had disappeared. A comparative test using extracted pore water did not indicate any effect of the permeant on the test result. Gradients in the order of 5–20 were applied by means of mercury pots connected to inflow and outflow back-pressured burettes. The pore pressure difference Δu necessary to create the selected gradient was applied in the form of $+\Delta u/2$ at the base and $-\Delta u/2$ at the top of the specimen. The test data were interpreted accounting for the change in gradient due to the changing weights of the fluid columns in the in- and outflow burettes, as well as for the observed differences in in- and outflow volumes, using the method discussed by Tavenas *et al.* (1983). A volume of water of 15–30% of the total volume of the specimens was circulated and repeatable gradient–velocity relations were generally observed during the final half to two-thirds of the circulation. The void ratio e_o of the specimen was obtained from water content measurements on the trimmings cut during specimen preparation, accounting for the observed volume changes during consolidation to the *in-situ* stresses. Given the size of the specimen, such estimates of e_o may not be totally representative, particularly for the 200 mm specimens.

TABLE 1. Properties of the investigated clays

Site	Depths (m)	w (%)	w_L (%)	w_p (%)	I_p (%)	I_L	% < 2μ	σ_p' (kPa)	C_c
				Champlain sea clays					
St-Zotique	2.00	91	61	25	36	1.8	80	50	6.0
	to	to	to	to	to	to	to	to	to
	17.00	63	43	23	20	2.2	60	240	2.0
Fort Lennox	6.10	79	70	22	48	1.2	81	180	3.0
St-Hilaire	9.50	69	55	23	32	1.4	71	125	4.0
Mascouche	3.80	61	55	24	31	1.2	76	290	2.8
Louiseville	2.90	79	71	27	44	1.2	77	80	3.7
	to	to	to	to	to	to	to	to	to
	26.00	60	59	25	34	0.8	85	300	2.2
Batiscan	5.50	80	35	22	17	2.6	77	80	2.2
	to	to	to	to	to	to	to	to	to
	20.50	71	54	24	31	1.5	91	190	4.5
St-Thuribe	6.90	52	44	22	22	1.3	44	195	1.2
St-Alban	1.90	90	53	25	28	2.7	78	40	2.5
	to	to	to	to	to	to	to	to	to
	7.80	40	28	18	10	2.0	31	100	1.2
				Other Canadian clays					
B2	4.90	31	30	15	15	1.4	36	150	0.3
	to	to	to	to	to	to	to	to	to
	13.10	38	20	14	06	2.9	43	105	0.5
B6	2.80	53	24	14	21	2.1	76	130	0.7
	to	to	to	to	to	to	to	to	to
	13.40	29	44	25	09	0.9	51	180	0.3
Matagami*	1.90	108	74	25	49	2.3	91	55	5.6
	to	to	to	to	to	to	to	to	to
	10.30	48	48	28	20	1.4	65	90	1.2
				Other clays					
Atchafalaya	20.80	65	99	37	62	0.5	76	160	1.1
Bäckebol	5.40	81	74	28	46	1.1	59	55	2.2
Lilla Mellösa	4.30	104	111	38	73	0.9	63	40	3.1

*Properties measured on bulk specimen.

The oedometer tests were performed in a common cell, modified as indicated by Tavenas *et al.* (1983) to provide a tight connection at the base of the specimen. The consolidation load was applied in 24 h stages with a load increment ratio of 1.5. After each 24 h consolidation period, for stresses in excess of σ_{vo}', the oedometer frame was blocked to maintain a constant void ratio in the specimen and a falling head test was carried out over a period of 24 h, starting from an initial head of about 0.75 m, i.e., an initial gradient of about 39. The void ratios were computed from the dry weight of the entire specimen.

The index properties of the clays tested, grain size distribution, w_p, w_L, I_p, I_L, were measured on material obtained from the 200 mm specimen during the preparation of the smaller triaxial and oedometer specimen.

This test program was applied to all clays but the Saint-Zotique, Fort Lennox, Mascouche, and Saint-Alban Champlain sea clays, where only falling head tests in the oedometer were carried out at various depths. At some sites, the program was performed at two or more different depths.

All tests were performed in an air-conditioned laboratory, at a controlled temperature of 21 ± 0.5°C. Permeability data presented herein correspond to that condition.

3. Properties of the investigated clays

Intact soft clays from 14 different sites in Canada, the USA, and Sweden were investigated to cover a wide range of geological origin, mineralogical composition, and index properties and preconsolidation and resulting structure. The main properties of the investigated clays are given in Table 1.

The 8 Champlain sea clay sites are identified in Fig. 1. Their geographical distribution makes them representa-

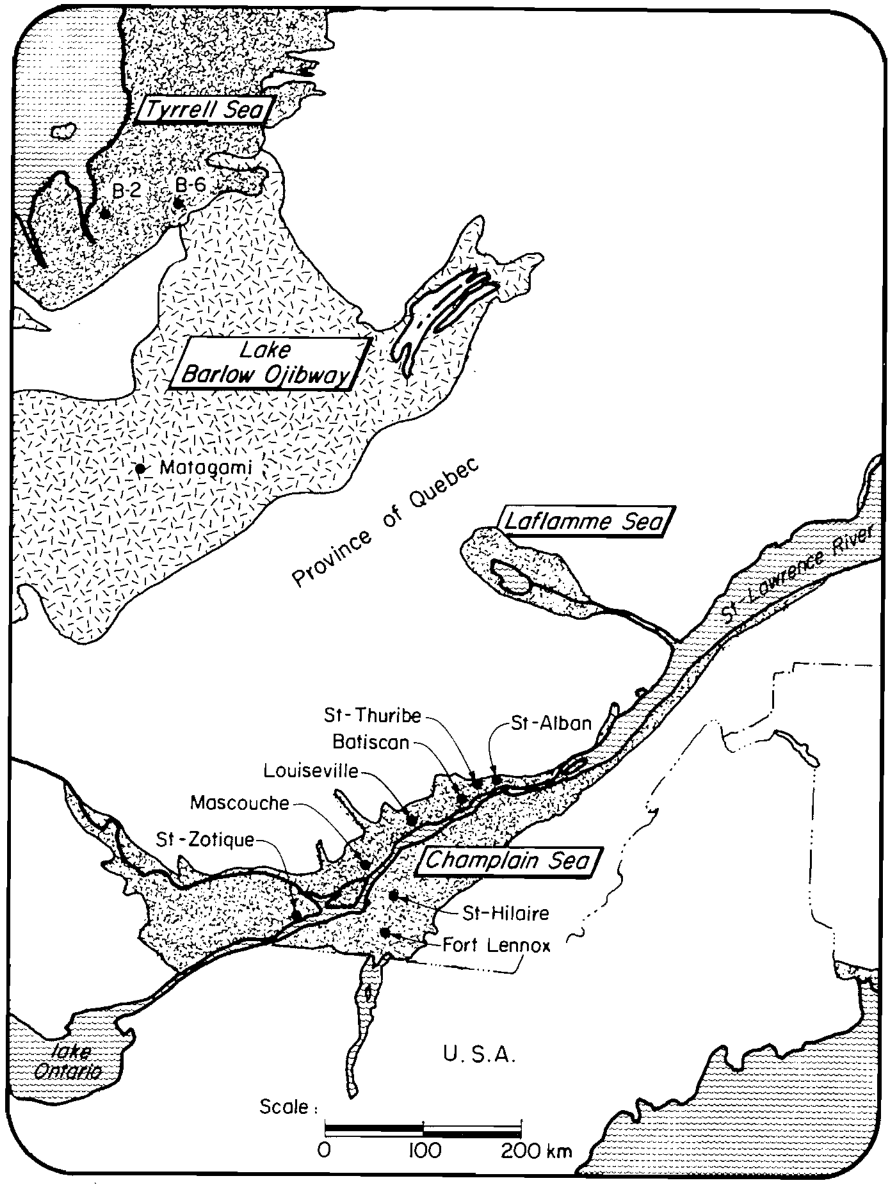

FIG. 1. Location of clay deposits investigated in Canada.

tive of the entire Champlain sea formation. Champlain sea clays were deposited in a marine environment during the retreat of the Wisconsin glaciers, 12 000 – 10 000 years ago. Sediments originated mainly in the Precambrian Laurentian shield, with some contribution from the Appalachian in the south of the sedimentation basin. In the center of the Saint Lawrence valley the clays are fine grained soils of medium to high plasticity, with clay mineral contents in the order of only 10–45% and consisting mainly of illite and mica (Lebuis *et al.* 1982). At the northern limit of the basin, the proximity of the Laurentians has resulted in coarser soils of low plasticity (Saint-Alban, Saint-Thuribe) which should be identified as rock flour rather than clays. The deposits are usually rather massive and homogeneous (Saint-Zotique, Saint-Hilaire, Louiseville, Saint-Thuribe) but they may be banded (Mascouche) or stratified (Fort Lennox, Batiscan, Saint-Alban). The Louiseville clay, typical of the central deposits, is remarkably homogeneous in all its properties over the full investigated depth range of 26 m. The Champlain sea clays are overconsolidated with an OCR in the order of 1.5–4 and present a stiff and brittle structure (Leroueil *et al.* 1979).

The B2 and B6 sites along the Broadback river (Fig. 1) were deposited in the Tyrrell sea in the final stages of retreat of the Wisconsin ice sheet, about 7000 years ago.

The sediments result from the abrasion of the Precambrian Laurentian shield and have formed coarse materials of very low plasticity which contain only limited amounts of illite and mica. These clayey silts or rock flours are usually banded and sometimes interstratified with sand. The B2 and B6 clays exhibit OCR in the order of 2–3 and an extremely stiff and brittle structure (Paré 1982).

The Matagami clay is typical of the varved clays deposited in the post glacial lake Barlow-Ojibway. The varves have a thickness in the order of 0.5–2 cm, often variable with depth. The clayey varves are fine grained and of high plasticity, while the coarser varves consist of silty clays of medium plasticity. The Matagami clay is generally more plastic, with thinner and finer varves than the New Liskeard clay tested by Chan and Kenney (1973). The Matagami clay has an OCR of about 2 and presents a structural behaviour similar to that of the Champlain sea clays.

The Atchafalaya clay is a recent organic deposit of the Mississippi delta in Louisiana, USA. The sampling site was located next to the sites investigated by MIT (Ladd and Foott 1974). The deposit is stratified with peat or highly organic layers, but at the test depth a relatively homogeneous layer of high plasticity clay was present. The Atchafalaya clay is nearly normally consolidated but recent investigations (Paré 1982) have shown that it presents all the features of a structured clay, even though to a lesser extent than the Champlain sea clays.

The Swedish clays are recent postglacial deposits. The Bäckebol site, near Göteborg on the Swedish west coast, is covered by a nearly normally consolidated clay of medium to high plasticity (Larsson 1981). The Lilla Mellösa clay, near Stockholm is typical of the clays along the Eastern central coast of Sweden: it is a highly plastic nearly normally consolidated clay (Chang 1982). Recent studies at Laval University (Brousseau 1983) have shown that, in spite of their very low preconsolidation, these clays behave as structured clays, but to a lesser extent than that reported by Leroueil *et al.* (1979) for Champlain clays.

As can be seen in Table 1, the range of soft clays considered in this study is characterized by clay fractions of 31–91%, plasticity indices of 6–73%, liquidity indices of 0.5–2.9, and preconsolidation pressures of 40–300 kPa. While highly overconsolidated clays are excluded, the soft to firm clays tested are believed to represent a wide range of natural clay deposits.

4. Definition of the type of permeability – void ratio relation

The permeability of porous media is related to the size, shape, and distribution of their voids. For sands the relevant relationship was developed by Kozeny (1927) and Carman (1956) and is written in the form:

$$[1]\quad k = \frac{1}{K_o T^2 S_o^{\,2}}\,\frac{\gamma}{\mu}\,\frac{n^3}{(1-n)^2}$$

where k = permeability, K_o = pore shape factor, T = tortuosity of the flow path, S_o = specific surface of the grains of the soil, n = soil porosity, γ = density of the permeating fluid, and μ = viscosity of the permeating fluid.

Taylor (1948) showed that [1] was valid only for sands and could not be applied to clays. More recently, Samarasinghe *et al.* (1982) have suggested that a slightly modified version of [1],

$$[2]\quad k = C\frac{e^n}{1+e}$$

would be generally applicable to normally consolidated clays, with the power n typically in the order of 4–5, while C is a reference permeability indicating the soil characteristics.

Having noted the limitations of [1] when applied to clays, Taylor (1948) suggested an empirical linear relationship between the logarithm of k and the void ratio, i.e.,

$$[3]\quad \lg k = \lg k_o - \frac{e_o - e}{C_k}$$

where C_k is a permeability change index and k_o, e_o are the *in-situ* values. This type of relationship has become the most common way of expressing the variation of the permeability of clays with void ratio, Mesri and Rokhsar (1974) noting that it would be generally valid for the range of void ratio changes encountered in engineering practice.

For a very wide range of void ratio, [3] may not be consistently valid and Mesri and Olson (1971) were led to suggest the use of a linear relationship between lg k and lg e:

$$[4]\quad \lg k = A \lg e + B$$

Equations [1]–[4] were generally developed from tests on artificial or remolded soils, and their applicability to initially intact natural clays must be assessed.

The experimental data obtained in the present investigation suggest that any of [2]–[4] may be valid for certain clays or certain ranges of void ratio variations, and not applicable in other circumstances. As shown in Fig. 2, in the Batiscan clay, [3] seems to be well representative of the reduction of permeability when the clay is compressed from a void ratio of 2.13–1.3, i.e., for a volumetric strain of 27%. On the other hand, the lg e vs. lg k relation presents a well-defined curvature. On the contrary, the Bäckebol clay exhibits a curved e vs. lg k relation (Fig. 3) while it behaves exactly in conformity with [4] over the wide range of void ratios investigated. Finally, as shown in Fig. 4, [2] would be the most

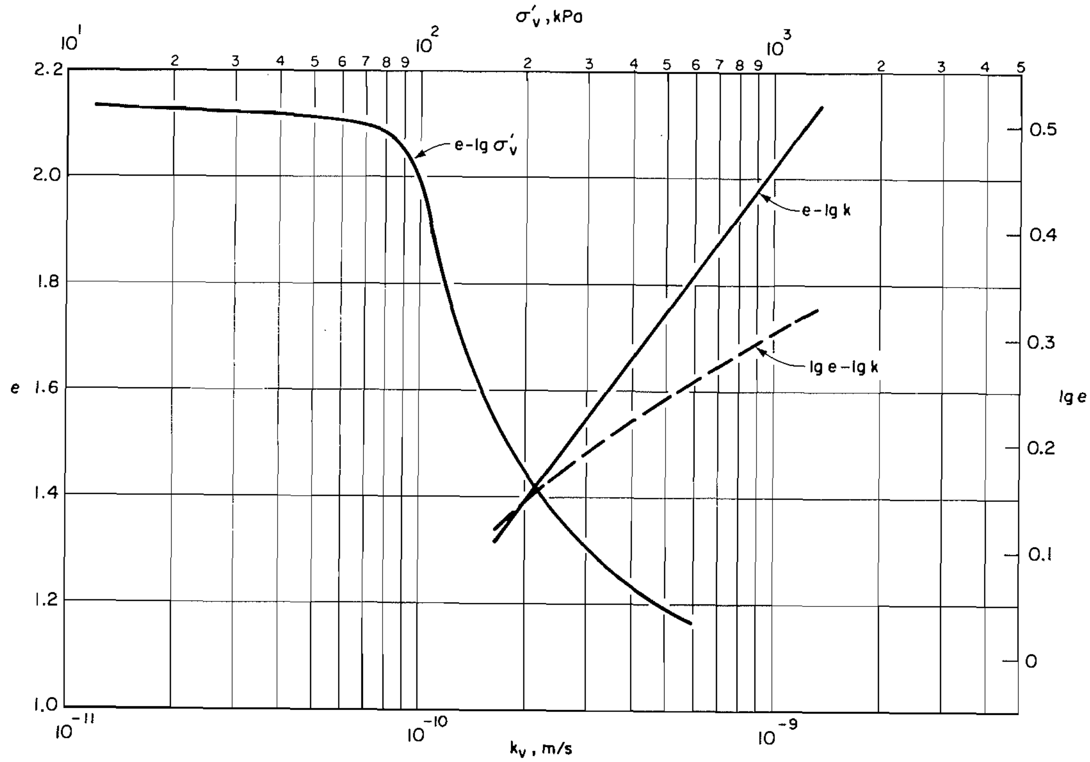

FIG. 2. Variation of permeability with void ratio. Batiscan clay.

suitable to represent the k–e relation of the Matagami clay subjected to very large volumetric strains (48%) and void ratio changes. From these few examples, it may be concluded that none of the e–k equations [1]–[4] is generally valid and thus fundamentally superior to the others.

To further investigate this matter, a special CRS oedometer test was carried out on an intact specimen of Louiseville clay. The test was interrupted at every 1% strain from 0 to 12% and at every 2% strain from 12 to 32% strain. At each interruption, a falling head test was performed over a 20 h period, under nearly constant specimen height and void ratio. The purpose of this test was to obtain a detailed e–k relation and to check the eventual effects of structural changes when a structured clay becomes normally consolidated. The e vs. lg σ_v' and different e–k relationships obtained from the test are shown in Fig. 5. The e–σ_v' curve is typical of structured Champlain clays with a sharp break at the preconsolidation pressure, a very high compressibility immediately beyond σ_p', followed by strongly reduced C_c values for strain in excess of 18%. The permeability data show very little scatter and the e–k relation fits a linear e vs. lg k relationship very well (eq. [3]) for strain of 0–20%; at larger strains the e vs. lg k relation exhibits a certain curvature. The change in shape of the e vs. lg k relation corresponds roughly to the change in slope of the e vs. lg σ' relation. This could reflect a fundamental change in the structural arrangement and behaviour of the clay at strains in excess of 20%: consistent with Olsen's (1962) model of particle aggregates creating macro- and micropores, one could associate the initial behaviour to the change in shape and size of the macro-pores while the behaviour at strains in excess of 20% would result from structural changes affecting both macro- and micropores. This assumption obviously needs verification by means of porosimetry and electron microscope studies such as those developed by Delage (1977). One important consequence of such possible changes in structural arrangement of a natural clay is that the turtuosity (cf. eq. [1]) would also vary and invalidate the existence of a simple, unique e vs. k relationship. As shown in Fig. 5, [2] and [4] do not properly represent the behaviour of the Louiseville clay, at any stage of compression.

The available experimental evidence suggests that none of the e–k equations proposed earlier are of general validity and take into account the probably complex behaviour of the structure of intact natural clays when they become normally consolidated. Therefore, when adopting a void ratio – permeability equation, emphasis

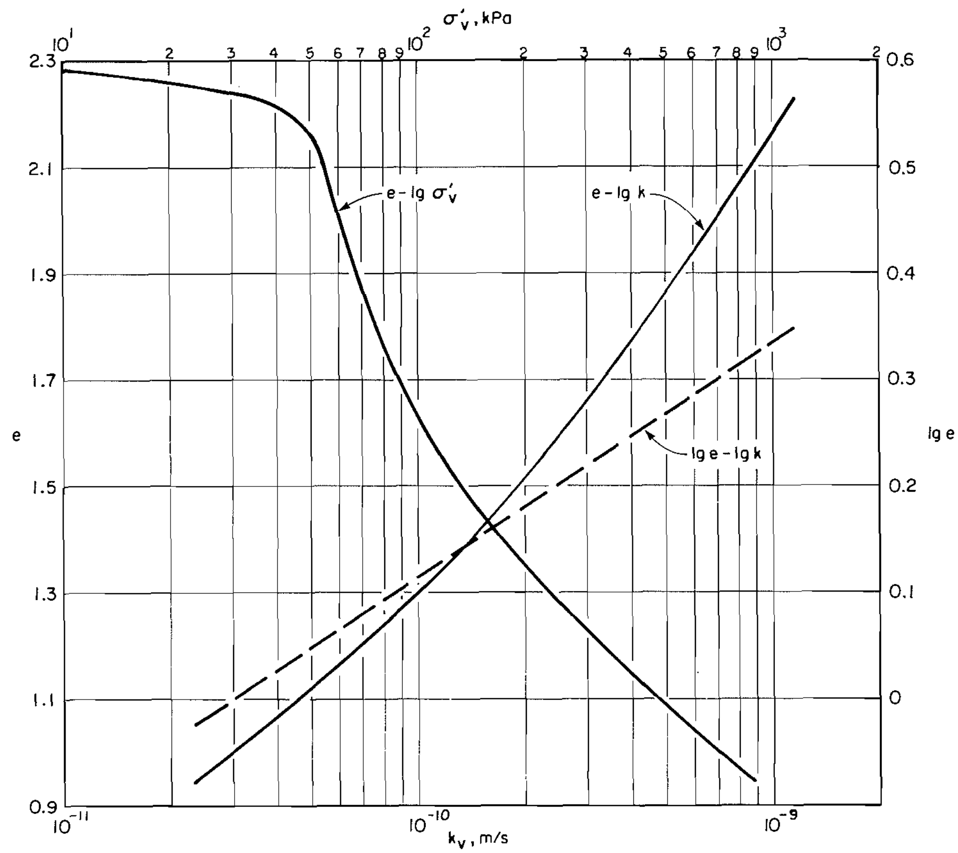

FIG. 3. Variation of permeability with void ratio. Bäckebol clay.

should be put on simplicity and practical relevance. In this sense, the linear e vs. lg k equation [3] appears as a logical choice. First of all it completely describes the permeability behaviour in terms of the initial conditions e_o, k_o and of a permeability change index C_k which are easy to measure and to handle. In addition, as noted by Mesri and Rokhsar (1974) or Mesri and Tavenas (1983), and as will be further evidenced herein, a linear e vs. lg k relation is a good representation of the behaviour of most natural soft clays for strains of less than 20%, i.e., for strains of practical relevance in most engineering problems.

It was therefore decided to describe the permeability characteristics of the natural soft clays tested in the present study in terms of [3]. In the following sections, the *in-situ* conditions e_o, k_{vo}, k_{ho}, and the factor affecting them are considered; the permeability change index C_k is separately investigated.

5. Permeability at the initial conditions

The experimental data obtained from such a variety of soft clays as listed in Table 1 may be used to gain some insight into the factors affecting the permeability of natural soft clays at the *in-situ* conditions, referred to as the *in-situ* permeability k_o.

5.1. *Parameters governing* e_o *vs.* k_{vo}

In accordance with Kozeny–Carman equation, the permeability of any soil is directly related to the size of the voids, i.e., the porosity or void ratio, the shape of the voids related to the shape, specific surface, and arrangement of the soil particles, and the tortuosity of the flow path which directly represents the distribution of the voids.

In a homogeneous clay deposit with uniform grain size distribution and mineralogy, formed in a stable deposition environment, one could expect a relatively uniform structural arrangement. Thus, the porosity would be the only variable to affect the change in permeability with depth. Such ideal deposits seldom exist. However, two of the investigated sites showed a reasonably well-defined relationship between the *in-situ* void ratio and the *in-situ* vertical permeability. As shown in Fig. 6, k_{vo} at B6 was observed to decrease with the void ratio following a linear e vs. lg k relation with

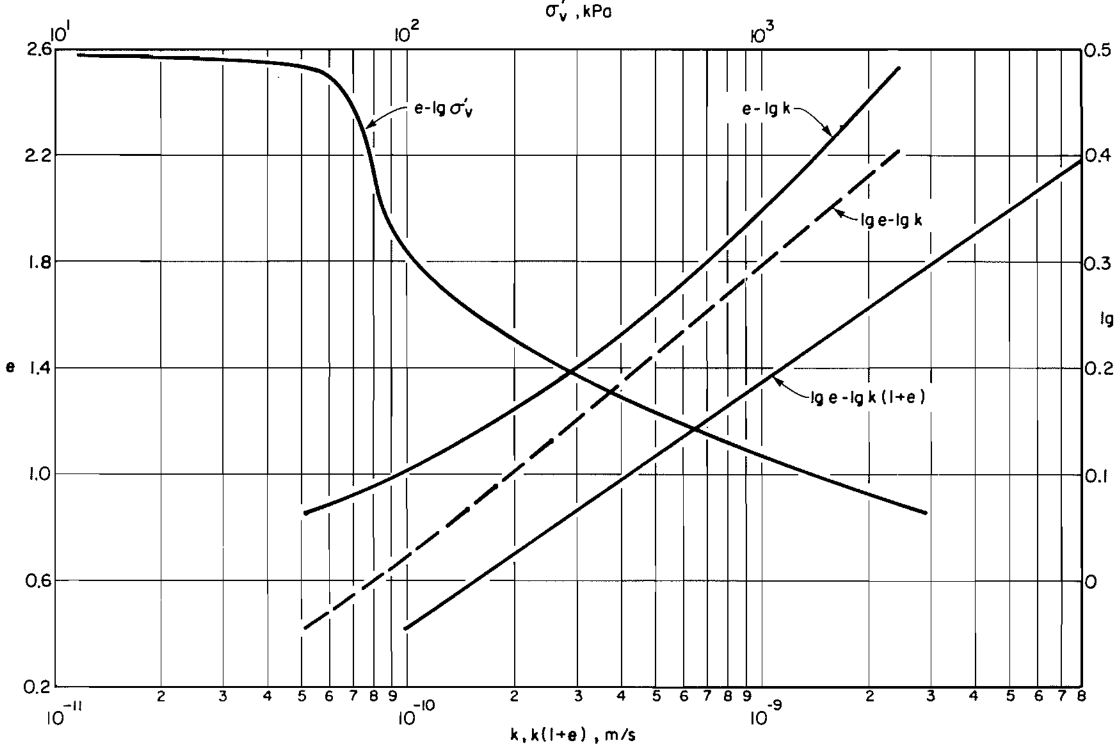

FIG. 4. Variation of permeability with void ratio. Matagami clay.

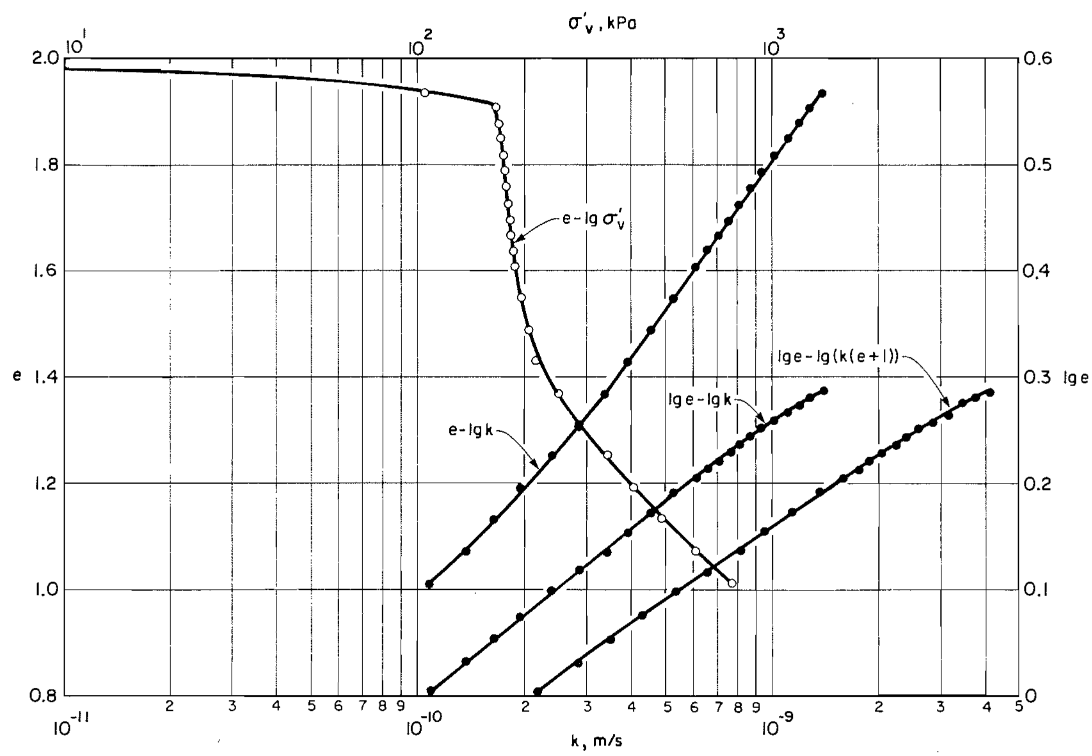

FIG. 5. Detailed study of the k–e relation. Louiseville clay.

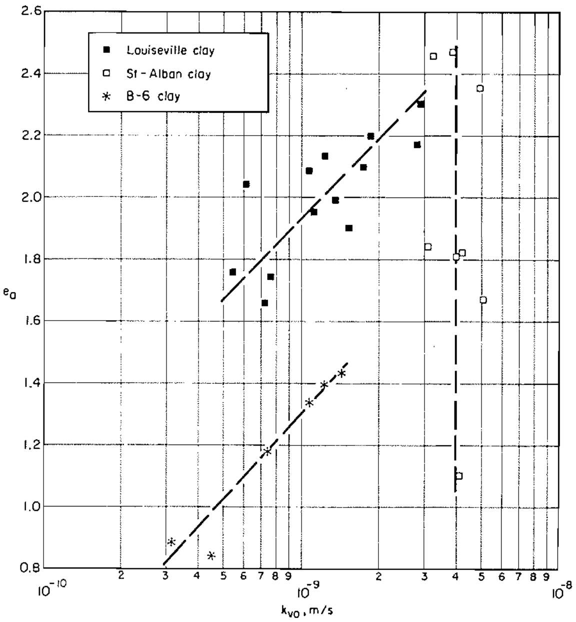

FIG. 6. Relations between k_{vo} and e_o at Louiseville, B6 and Saint-Alban.

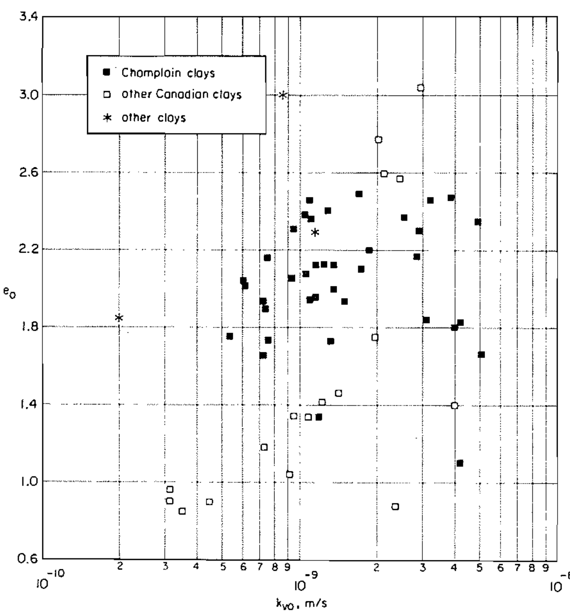

FIG. 7. The k_{vo}–e_o relation for all clays tested.

little scatter; at Louiseville, the data is somewhat scattered, but a trend for k_{vo} to decrease with e_o following a linear e vs. lg k_v relation similar to that observed on any specimen of that clay (Fig. 5) is clearly observed. On the other hand, at Saint-Alban, the deposit exhibits a reducing clay fraction and a decreasing plasticity index with depth as the clay progressively changes into a silty material; as a result, the effect of

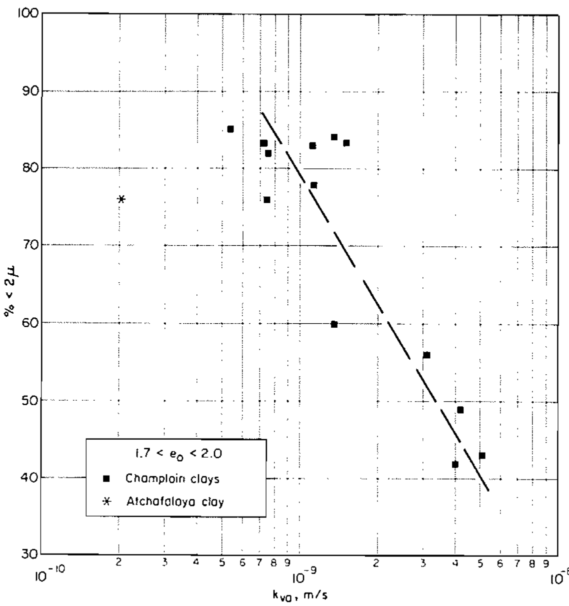

FIG. 8. Relation between k_{vo} and the clay fraction for clays with $1.7 < e_o < 2.0$.

reducing void ratio is compensated by changes in the void shape and tortuosity so that the *in-situ* permeability is nearly constant with either depth or void ratio. Thus, relationships between e_o and k_{vo} should not generally be expected, except in extremely homogeneous deposits. This is confirmed by the compilation of all data obtained in the present study in Fig. 7: no correlation or trend between k_{vo} and e_o may be defined.

Besides the void ratio, the grain size is well established as a significant parameter, with the permeability increasing proportionally to the square of a significant grain diameter (Taylor 1948). In clayey soils, the clay fraction (CF = % of particles less than 2μ) is the common parameter for qualifying the grain size, and a certain relationship between CF and k_{vo} could be expected, at a given void ratio, provided the mineralogies and deposition environments were similar. As shown in Fig. 8, permeabilities measured in Champlain clays with void ratios in the range of 1.7–2.0 support this contention and exhibit a clear trend for k_o to increase with decreasing clay fraction; on the other hand the Atchafalaya clay with different mineralogy and deposition environment has a much lower permeability as a result of differing tortuosity and specific surface. Thus, while significant for clays in a specific geological environment, the clay fraction is not simply and directly related to k_{vo} when considering a wide variety of clays. This is confirmed by Fig. 9 showing the data developed in the present study, separated in void ratio classes: no trends may be detected.

It is obvious, both from [1] and from the data in Figs.

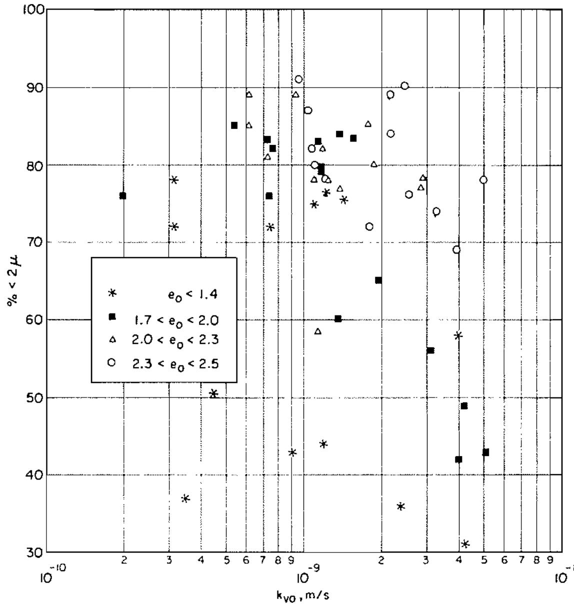

FIG. 9. The k_{vo} – clay fraction relation for all clays tested.

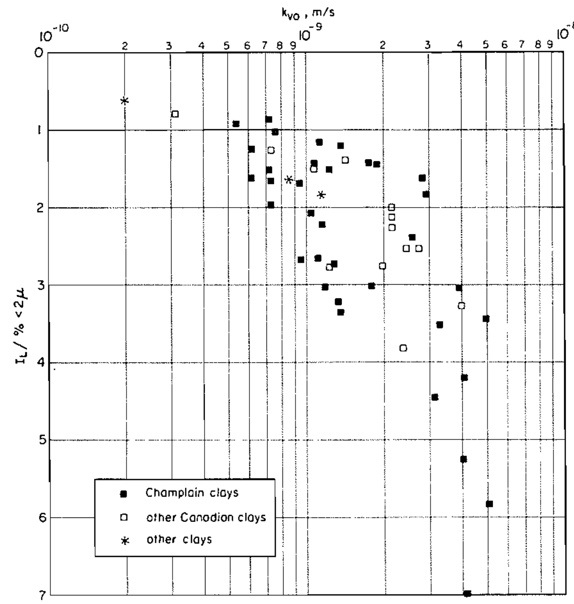

FIG. 10. Relation between k_{vo} and the empirical parameter I_L/clay fraction.

6–9 that the *in-situ* permeability in a clayey soil is governed not only by its void ratio and grain size but also by the shape and distribution of the voids, i.e., by the fabric of the clay. It is not easy at present to define simple parameters describing the fabric of a natural, structured clay. Porosimetry appears as a promising avenue of development (Delage 1977) but is not sufficiently advanced yet. The parameters available at present relate to the soil's grains rather than the pores, but the plasticity index I_p and the liquidity index I_L may represent to some extent the shape of the pores and the fabric of the soil. Thus an attempt to relate k_{vo} to an empirical parameter including the effects of void ratio, grain size, and structure, and defined as the ratio I_L to clay fraction, was made. The experimental data is shown in Fig. 10: in spite of a significant scatter, a certain trend may be identified for k_{vo} to decrease with decreasing I_L/clay fraction, and this irrespective of the type of clay considered.

In conclusion, the permeability of a natural soft clay at its *in-situ* void ratio and structure is dependent on a series of variables, the most significant of which, the fabric, is not easily assessed or quantified. The empirical parameter I_L/clay fraction attempts to account for the major variables but it is obviously not sufficient: the resulting relation to k_{vo} (Fig. 10) is too scattered to be used as a design tool, but it has an indicative value. On the other hand, measuring k_{vo} is a sufficiently simple operation in the laboratory to eliminate the need for accurate methods of predicting k_{vo} from other clay properties.

5.2. *Permeability anisotropy*

In view of their mode of deposition, natural clays are often considered to necessarily present a permeability anisotropy. Experimental data to confirm this "logical assumption" is scarce and rather contradictory. Olson and Daniel (1981) compiling data from different sources indicate values of r_k typically in the range of 1–1.5 for marine clays, and of 1.5–40 for varved clays. The few recent and reliable studies suggest that anisotropy may be very small if at all present. Chan and Kenney (1973) testing the New Liskeard varved clay with thick, extremely contrasting clayey and silty layers, which should maximize the permeability anisotropy, measured an anisotropy ratio $r_k = (k_{ho}/k_{vo})$ of only about 3. Larsson (1981) testing a great number of Swedish clays concluded to the isotropy of these soils with the differences between k_{ho} and k_{vo} in the range of the measurement error. Permeability anisotropy was investigated using 50 mm triaxial tests and oedometer tests on vertical and horizontal specimens cut from the same 200 mm triaxial specimen.

At one depth on the B6 clay, oedometer specimens were cut horizontally to measure k_{vo}, vertically to measure k_{ho}, as well as at two intermediate inclinations. The results are shown in Fig. 11. The values of k_o are in the range of 1.09×10^{-9} m/s for the vertical permeability to 1.29×10^{-9} m/s at 45° inclination; the anisotropy ratio r_k is equal to 1.16. In view of the small scale variability of oedometer specimens, it is debatable whether such variations are significant and one could

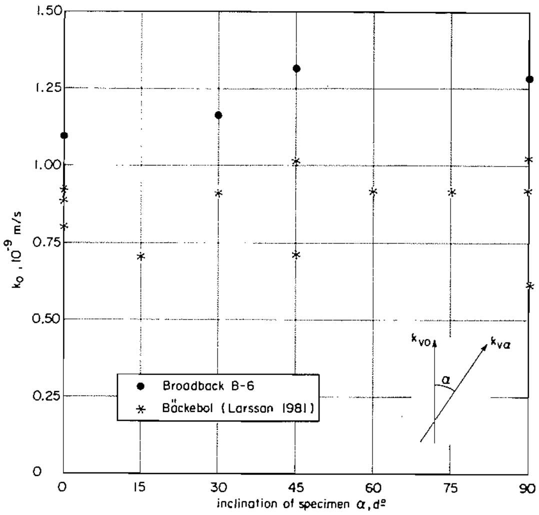

FIG. 11. Variation of k_o with the orientation of the specimen at B6 (this study) and Bäckebol (Larsson 1981).

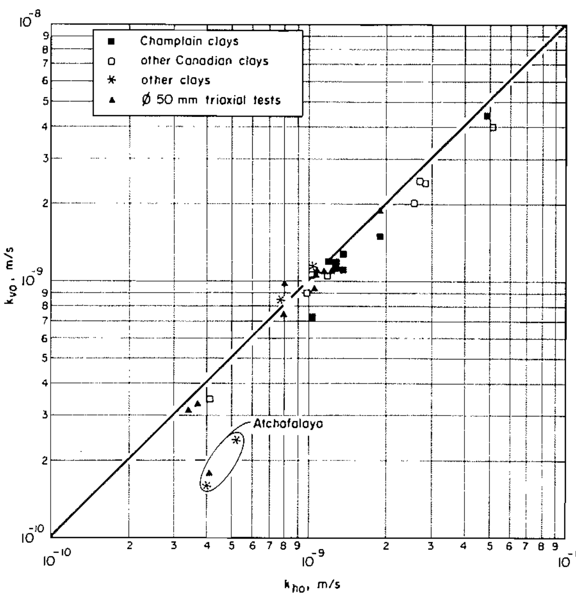

FIG. 12. Comparison of vertical and horizontal permeabilities in intact natural clays.

conclude to the negligible anisotropy of permeability of this marine clay. Similar results and conclusions were obtained by Larsson (1981) on the Bäckebol clay, as indicated in Fig. 11.

The results of oedometer and triaxial tests for the different clays investigated here are presented in Fig. 12. With the exception of the Atchafalaya clay where the anisotropy seems to be significant (r_k = 2.2–2.5), the horizontal permeability is not much different from the vertical. In the oedometer tests the anisotropy ratio was found to vary between 0.91 and 1.42 with an average of 1.10. In the somewhat larger triaxial specimens, r_k was observed in the range of 0.81–1.16 with an average of 1.03. It would thus appear that some of the observed anisotropy is actually due to specimen variability. The results suggest that permeability anisotropy is not a significant parameter in most massive marine clays.

The Matagami varved clay was also tested using the same procedure and anisotropy ratios in the order of 1.2–1.3 were obtained. However, the use of circular specimens as well as other experimental problems pointed out by Chan and Kenney (1973) make this result questionable. On the other hand the varves in the Matagami clay are much thinner and less differentiated in terms of grain size than those in the New Liskeard varved clay, so that one would expect r_k much less than the values of 2–3 reported by Chan and Kenney (1973).

6. Permeability – void ratio relationships

As discussed earlier none of the existing permeability – void ratio relationships are generally valid, but the linear e vs. lg k relation appears as a reasonable and practical approximation in the range of volumetric strains encountered in engineering practice. The variations of k with void ratio during the compression of the natural soft clays investigated here are described using [3], i.e., in terms of the permeability change index C_k.

6.1. e *vs. lg* k *relationships*

Figure 13 presents typical e vs. lg k relationships observed on the 8 different Champlain sea clay deposits. As already discussed (cf. Fig. 5) the e vs. lg k relations are prefectly linear for volumetric strains in the range of 0–20%. Beyond that a more or less significant curvature is observed, indicating a faster reduction of permeability with void ratio. The experimental curves are well ordered in the e vs. lg k space according to the grain size and plasticity characteristics of the clays: low I_p and clay fraction correspond to low curves, high I_p and clay fraction to high curves. The slope C_k of the curves also appears to vary with the initial void ratio so that the curves have a tendency to converge at low void ratios.

Figures 14 and 15 present the same data for the other Canadian clays and the American and Swedish clays respectively. Again here, the validity of a linear e vs. lg k relationship in the range of strains of practical interest is confirmed, even though a slight curvature may be observed on the Lilla Mellösa clay and, to a minimal extent on some specimens of Matagami clay. It would appear that an initial void ratio e_o = 2.5 is an upper limit for the strict validity of a linear e vs. lg k relation in natural clays. Consistent with the results on Champlain sea clays, the e vs. lg k curves are well ordered in terms of plasticity indices and clay fractions. The Tyrrell Sea

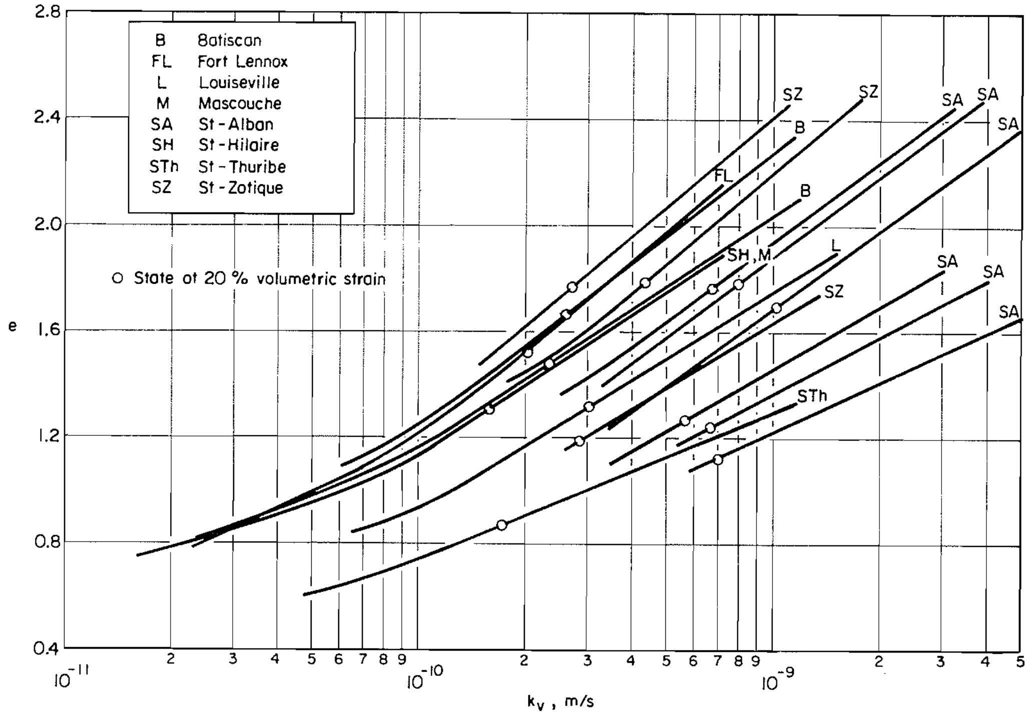

FIG. 13. The e vs. lg k_v relationships for Champlain sea clays.

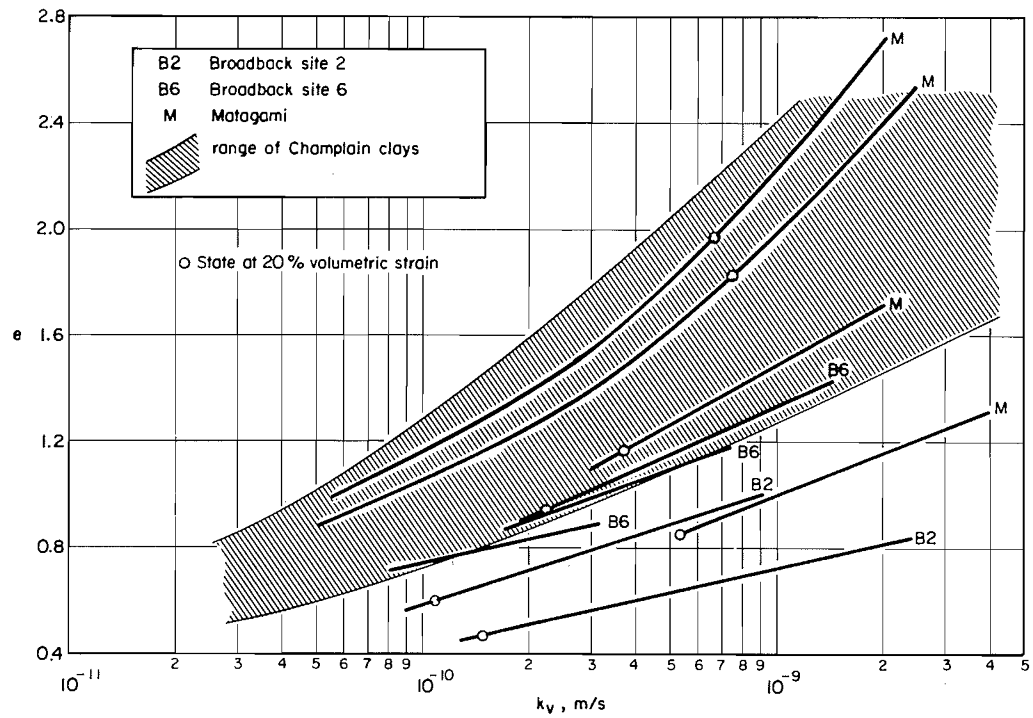

FIG. 14. The e vs. lg k_v relationships for other Canadian clays.

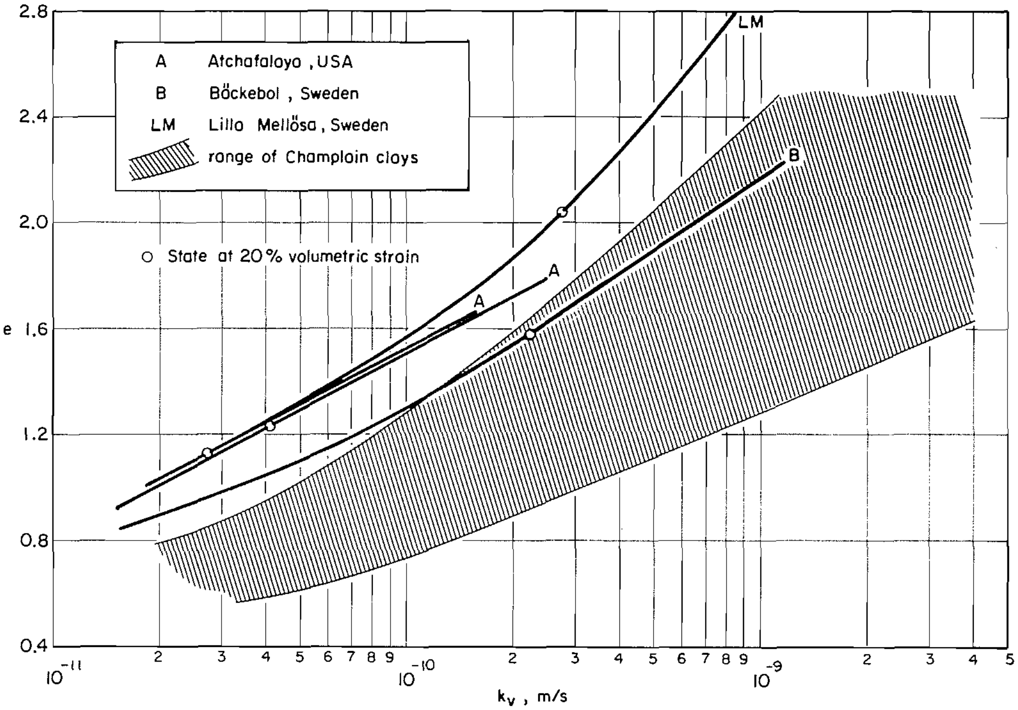

FIG. 15. The e vs. lg k_v relationships for Atchafalaya and Swedish clays.

clays with very low plasticity indices and clay fractions exhibit e vs. lg k relations well below those of the more clayey Champlain sea deposits. The Matagami varved clay is generally of high plasticity and falls in the upper range of Champlain sea clays, with the exception of the dense, low plastic crust and a deep more silty specimen. Atchafalaya clay and the Swedish marine clays are fine grained materials of high plasticity and their e vs. lg k relations fall well above those of the Champlain sea clays.

The position of the e vs. lg k curve in that space is the best indicator of the intrinsic permeability of a clay: the higher and more to the left the curve, the less pervious the clay. Discussing the *in-situ* permeability data, it was pointed out that the plasticity index and the clay fraction CF were significant parameters in determining the magnitude of k. The preceding discussion of Figs. 13–15 indicates that I_p and CF more generally govern the position of the e vs. lg k curves. Indeed, analysing all available data, it was found that the experimental curves are very well ordered according to a parameter I_p + CF; the resulting typical e vs. lg k curves for selected values of this parameter are shown in Fig. 16. Figure 16 could be used together with Fig. 10 for preliminary estimates of e vs. k relations in natural clays, even though direct measurements of k are sufficiently simple to be economically and technically justified.

6.2. *Permeability change index* C_k

For all tests, C_k was defined as the slope of the e vs. lg k curve for volumetric strains less than 20%.

In discussing Figs. 13–15, it was noted that the slope C_k seems to be directly related to the initial void ratio of the clay. The experimental data shown in Fig. 17 indeed confirms the existence of a simple correlation between C_k and e_o. A detailed analysis could lead to a second degree equation, but in the range of initial void ratios of interest, i.e., 0.8–3.0, a simple linear relation:

$$[5] \quad C_k = 0.5 e_o$$

appears as a reasonable and practical approximation. Equation [5] is considered sufficiently reliable to limit the experimental investigation to the measurement of e_o and k_{vo} for most practical problems involving consolidation and permeability changes.

Mesri and Rokhsar (1974) have suggested a correlation between the compression index C_c and the permeability change index C_k. Defining C_c from the e vs. lg σ' curves between σ_p' and a 20% volumetric strain, i.e., in the same range of void ratio as C_k, the experimental C_c/C_k values were observed to vary between 0.5 and 5, more or less as a function of the initial void ratio (Fig. 18). In Champlain sea clays, C_c/C_k is typically in the order of 3.0; it is less in the less structured Atchafalaya and Swedish clays. The data in Fig. 18 are rather

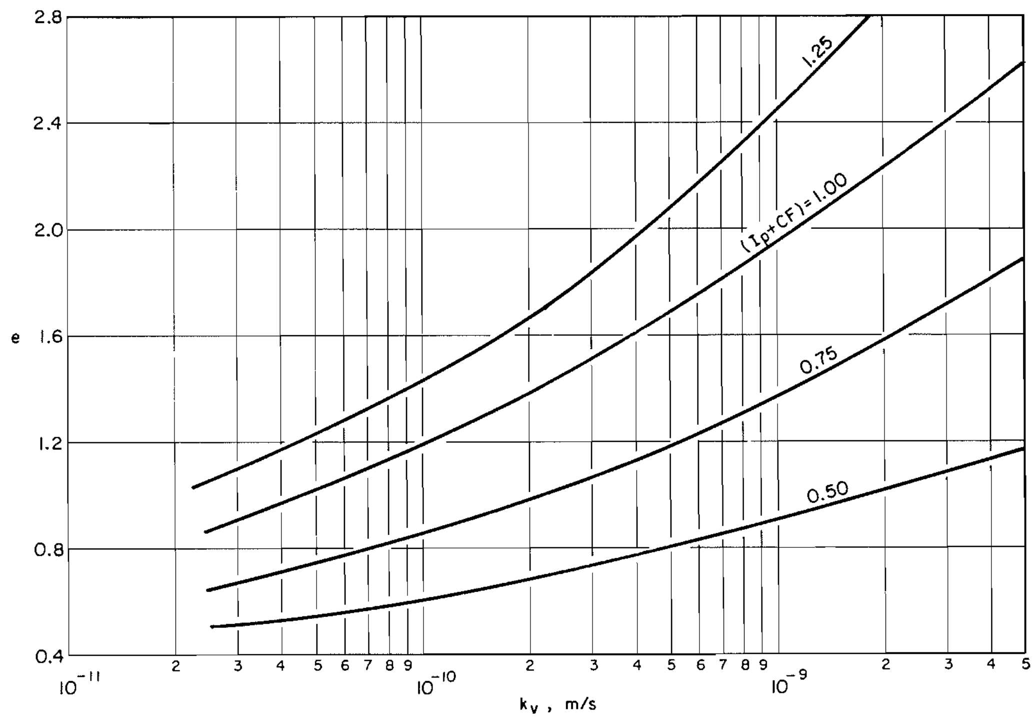

FIG. 16. Ranges of e vs. lg k_v relationships as a function of the empirical parameter I_p + clay fraction.

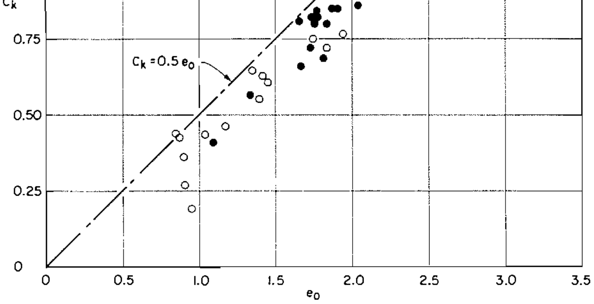

FIG. 17. Relation between the permeability change index C_k and e_0 for all clays tested.

scattered and it appears preferable to evaluate C_k from [5] than from C_c, particularly if one considers the simplicity of e_0 evaluation and the sensitivity of C_c to such factors as sampling disturbance, load increment ratio, and details in drawing and interpreting the e vs. lg σ_v' curve.

The data in Fig. 17 may be used to assess the validity of the assumption of a constant C_v in Terzaghi's consolidation theory. Since

$$C_v = \frac{k\sigma'(1+e)}{0.434\gamma_w C_c}$$

the condition for a constant C_v during consolidation may be written

$$\frac{1}{C_c} - \frac{1}{C_k} = \frac{1}{1+e}$$

The corresponding C_c/C_k vs. e relation is shown in Fig. 18. Only a few of the Tyrrell sea clay specimens did meet this requirement. In the great majority of cases, C_c/C_k are substantially higher, indicating that C_v should experience significant variations during consolidation.

7. Conclusion

A comprehensive experimental laboratory study on the permeability of intact soft clays from Canada, the USA, and Sweden has led to the following conclusions.

(1) None of the existing relations between permeability and void ratio is generally valid, irrespective of the

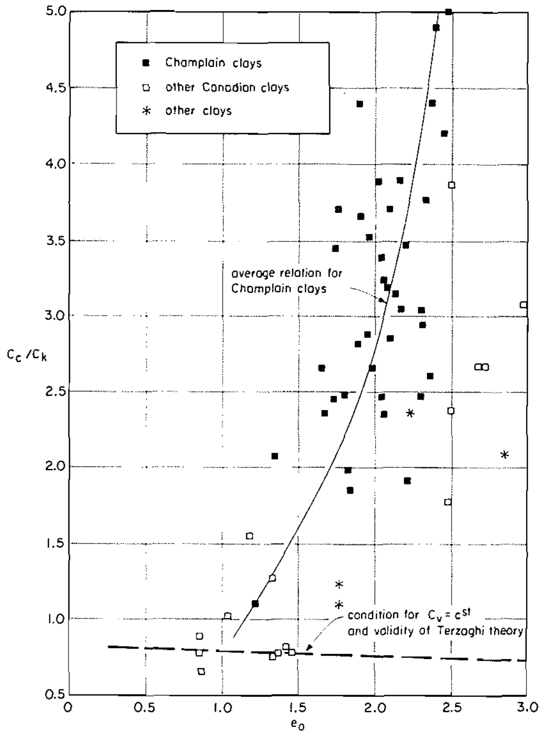

FIG. 18. Relation between C_c/C_k and e_o.

type of clay, the initial void ratio, or the range of void ratio change.

(2) From a practical point of view a relation

$$[3] \quad \lg k = \lg k_o - \frac{e_o - e}{C_k}$$

is excellent for initial void ratios less than 2.5 and for volumetric strains of practical interest in engineering problems. The merit of this linear relation is to limit the evaluation of permeability to the measurement of k_o and C_k.

(3) The permeability k_o of intact soft clays at their *in-situ* void ratio is a function not only of void ratio and grain size but also of the plasticity and the fabric of the clay. In the absence of simple means of quantifying clay fabric, k_o may be related to such parameters as the liquidity index. A trend was observed for k_o to increase with increasing ratio of I_L to clay fraction.

(4) Anisotropy is not a significant feature of the *in-situ* permeability of massive marine clays.

(5) The e vs. $\lg k$ relationships of all clays tested here are well ordered in the e vs. $\lg k$ space according to an empirical parameter I_p + CF; the higher the parameter, the less pervious the clay.

(6) The permeability change index C_k is simply correlated to the initial void ratio,

$$C_k = 0.5e_o$$

being a reasonable practical approximation.

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ABELEV, M. Y. 1973. Construction d'ouvrages sur les sols argileux mous saturés. Translated from Russian by J. P. Magnan, Technique et Documentation, Paris, 372 p.

AMAR, S., and DUPUY, H. 1973. Etude de la perméabilité des sols fins mesurée en laboratoire. Research Report No. 23, Laboratoire Central des Ponts et Chaussées, Paris, 34 p.

BROUSSEAU, P. 1983. Etude de l'état limite et de la déstructuration d'argiles naturelles de Suède et du Québec. Master's degree thesis (in preparation), Department of Civil Engineering, Laval University, Québec, P.Q.

CARMAN, P. C. 1956. Flow of gases through porous media. Butterworths, London.

CASAGRANDE, L., and POULOS, S. 1969. On the effectiveness of sand drains. Canadian Geotechnical Journal, **6**(3), pp. 287–326.

CHAN, H. T., and KENNEY, T. C. 1973. Laboratory investigation of permeability ratio of New Liskeard varved soil. Canadian Geotechnical Journal, **10**(3), pp. 453–472.

CHANG, Y. C. E. 1981. Long term consolidation beneath the test fills at Väsby, Sweden. Swedish Geotechnical Institute, Report No. 13, 148 p.

DELAGE, P. 1977. Etude du milieu poreux et de la texture d'argiles sensibles du Québec. Docteur-ingénieur degree thesis, Ecole Nationale Supérieure des Mines de Paris, Paris, 133 p.

EIGENBROD, K. E. 1975. Analysis of pore pressure changes following the excavation of a slope. Canadian Geotechnical Journal, **12**(3), pp. 429–440.

GOODALL, D. C., and QUIGLEY, R. M. 1977. Pollutant migration from two sanitary landfill sites near Sarnia, Ontario. Canadian Geotechnical Journal, **14**(2), pp. 223–236.

JACOBSON, B. 1955. Isotropy of clay. Géotechnique, **5**(1), pp. 23–28.

KENNEY, T. C. 1979. Discussion of "Stability of slopes in soft clays" by G. A. Leonards. Proceedings, 6th Pan Am Conference on Soil Mechanics and Foundation Engineering, Lima, Vol. 3, pp. 83–89.

KENNEY, T. C., and CHAN, H. T. 1973. Field investigation of permeability ratio of New Liskeard varved soil. Canadian Geotechnical Journal, **10**(3), pp. 473–488.

KOZENY, J. S. 1927. Über Kapillare Leitung des Wassers im Boden. Sitzungsberichte der Akadämie der Wissenschaften in Wien, Abteilung IIa, p. 136.

LADD, C. C., and FOOTT, R. 1974. New design procedure for stability of soft clays. ASCE, Journal of the Geotechnical Engineering Division, **100**(GT7), pp. 763–786.

LA ROCHELLE, P., and LEFEBVRE, G. 1971. Sampling disturbance in Champlain clays. Sampling of soil and rock, American Society for Testing and Materials, Special Technical Publication 483, pp. 763–786.

LA ROCHELLE, P., SARRAILH, J., TAVENAS, F., ROY, M., and LEROUEIL, S. 1981. Causes of sampling disturbance and design of a new sampler for sensitive soils. Canadian Geotechnical Journal, **18**(1), pp. 52–66.

LARSSON, R. 1981. Drained behavior of Swedish clays. Swedish Geotechnical Institute, Report No. 12, 157 p.

LEBUIS, J., ROBERT, J. M., and RISSMANN, P. 1982. Regional mapping of landslide hazard in Québec. International Symposium on Landslides, Linköping, Sweden.

LEFEBVRE, G., and POULIN, C. 1979. A new method of sampling in sensitive clay. Canadian Geotechnical Journal, **16**(1), pp. 226–233.

LEROUEIL, S., TAVENAS, F., BRUCY, F., LA ROCHELLE, P., and ROY, M. 1979. Behaviour of destructured natural clays. ASCE Journal of the Geotechnical Engineering Division, **105**(GT6), pp. 759–778.

MESRI, G., and OLSON, R. E. 1971. Mechanisms controlling the permeability of clays. Clays and Clay Minerals, **19**, pp. 151–158.

MESRI, G., and ROKHSAR, A. 1974. Theory of consolidation for clays. ASCE Journal of the Geotechnical Engineering Division, **100**(GT8), pp. 889–904.

MESRI, G., and TAVENAS, F. 1983. Discussion on "Permeability and consolidation of normally consolidated soils" by Samarasinghe *et al.* (1982). ASCE Journal of the Geotechnical Engineering Division, **109**(GT6), pp. 873–878.

OLSEN, H. W. 1962. Hydraulic flow through saturated clays. Proceedings, 9th National Conference on Clays and Clay Minerals. Clays and Clay Minerals, Vol. 9. Pergamon Press, New York, pp. 131–161.

OLSON, R. E., and DANIEL, D. E. 1981. Measurement of the hydraulic conductivity of fine-grained soils. Permeability and groundwater containment transport. American Society for Testing and Materials, Special Technical Publication 746, pp. 18–64.

PARÉ, J. 1982. Etude de l'état limite et de la déstructuration d'argiles naturelles de la Baie James et d'Atchafalaya. Master's degree thesis, Department of Civil Engineering, Laval University, Québec, P.Q.

RAYMOND, G. P., and AZZOUZ, M. M. 1969. Permeability determination for predicting rates of consolidation. Proceedings, Conference on In Situ Investigations of Soils and Rocks. British Geotechnical Society, London, pp. 195–203.

SAMARASINGHE, A. M., HUANG, Y. H., and DRNEVICH, V. P. 1982. Permeability and consolidation of normally consolidated soils. ASCE Journal of the Geotechnical Engineering Division, **108**(GT6), pp. 835–850.

TAVENAS, F., BRUCY, M., MAGNAN, J. P., LA ROCHELLE, P., and ROY, M. 1979. Analyse critique de la théorie de consolidation unidimensionnelle de Terzaghi. Revue Française de Géotechnique, No. 7, pp. 29–43.

TAVENAS, F., LEBLOND, P., JEAN, P., and LEROUEIL, S. 1983. The permeability of natural clays. Part I: Methods of laboratory measurement. Canadian Geotechnical Journal, this issue.

TAYLOR, D. W. 1948. Fundamentals of soil mechanics. John Wiley & Sons Inc., New York, 700 p.

WILKINSON, W. B. 1969. Discussion. Proceedings, Conference on In Situ Investigations in Soils and Rocks, British Geotechnical Society, London, pp. 311–313.