Canadian Geotechnical Research Site No. 1 at Gloucester

G.C. McRostie and C.B. Crawford

Abstract: A parcel of land just south of Ottawa at Gloucester has been the site of an unusual amount of geotechnical research over the past 45 years. The parcel was recently to have been placed on the open real estate market but has been saved for scientific purposes and is now designated as "Canadian Geotechnical Research Site No. 1 at Gloucester". This paper presents an outline of the research that has been conducted at the site, in four general divisions, namely compressibility, strength, deformation, and soil property improvement. It is hoped that the site will stimulate the development and evaluation of new tools and techniques, foster scientific cooperation and information exchange, and allow the results of research involving the site to improve the state of practice, education, and research.

Key words: sensitive clay, compressibility research, strength research, deformation research, soil improvement research.

Résumé : Un montant exceptionnel de recherche en géotechnique a été faite durant les 45 dernières années sur un morceau de terrain juste au sud d'Ottawa à Gloucester. Ce terrain devait jusqu'à récemment être vendu mais il a été sauvegardé à des fins scientifiques et est maintenant connu sous le nom « Site No. 1 de recherche canadienne en géotechnique à Gloucester ». Cet article présente les grandes lignes de la recherche effectuée, en quatre divisions générales, soit la compressibilité, la résistance, la déformation et l'amélioration des propriétés des sols. Il y a bon espoir que ce site va stimuler le développement et l'évaluation de nouveaux outils et techniques, entretenir une coopération scientifique et un échange d'information, et permettre à améliorer l'état de la pratique, l'éducation ainsi que la recherche avec les résultats obtenus à même les essais effectués sur le site.

Mots clés : argile sensible, recherche sur la compressibilité, recherche sur la résistance, recherche sur la déformation, recherche sur l'amélioration des propriétés des sols.

Introduction

In the southern outskirts of Ottawa, Canada, in Gloucester, Ontario, there is a parcel of land which has considerable geotechnical interest and can serve a very special purpose in the future. This parcel was part of a World War 2 Canadian Naval Training Centre and has been owned by the Department of National Defence of Canada since the 1940s. As part of the Government of Canada current policy of disposing of all excess land holdings, the site was scheduled to be put on the open real estate market and sold for suburban land development.

Little recognition was being given to the fact that an unusual amount of geotechnical research had been carried out on a 4 ha part of the base, but enquiries were made to the National Research Council of Canada (NRC), whose former Division of Building Research had spearheaded the research at the site. The NRC was not able to produce funds to purchase the site, nor were the two local universities, University of Ottawa and Carleton University. However, it was fortunate that Professor G.E. Bauer of Carleton University was able to encourage his university to make an offer. The offer was to accept ongoing responsibility for the research site provided it was given title or a long-term lease at a nominal cost. Professor K.T. Law and Dr. M. Bozozuk also played important roles in the negotiations. This arrangement has now been completed and the 4 ha parcel has been designated as "Canadian Geotechnical Research Site No. 1 at Gloucester."

A photograph of the substantial on-site marker monument and the texts of the marker plates are shown in Fig. 1.

There have already been six such sites established in the United States. The National Council of Geo-Engineering and Construction (Geo-Council) has chosen to call them "National Geotechnical Experimentation Sites" and they compose a system of well-characterized sites, available for full-scale geotechnical experiments. They are well diversified, with one in California, two in Texas, one in Illinois, one in Massachusetts, and the newest site, added in 1998, in Alabama.

The purposes of the Geo-Council sites and the Canadian Geotechnical Research Site No. 1 would be (*i*) to provide documentation to stimulate the development and evaluation of new tools and techniques to improve geotechnical practice, research, and education; (*ii*) to foster cooperation and information exchange between public agencies, universities, and the private sector; and (*iii*) to disseminate the results of research and testing at each research site to improve the state

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Fig. 1. Signage monument photograph and texts of monument plates.

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CANADIAN
GEOTECHNICAL
RESEARCH SITE
Nº 1

SITE Nº 1
DE RECHERCHE
CANADIENNE EN
GÉOTECHNIQUE

RESEARCH BEGAN IN 1954
SOIL IS A DEEP SENSITIVE
COMPRESSIBLE CLAY
PROPERTIES STUDIED INCLUDE
COMPRESSIBILITY, STRENGTH,
PERMEABILITY AND SENSITIVITY
RESEARCH CARRIED OUT BY
NATIONAL RESEARCH
COUNCIL OF CANADA,
UNIVERSITIES,
INDUSTRIAL RESEARCH GROUPS

LES RECHERCHES DÉBUTÈRENT EN 1954
LE SOL EST UN PROFOND DÉPÔT
D'ARGILE SENSIBLE ET COMPRESSIBLE
LES PROPRIÉTÉS ÉTUDIÉES PORTENT
SUR LA COMPRESSIBILITÉ, LA RÉSISTANCE,
LA PERMÉABILITÉ ET LA SENSIBILITÉ
LES RECHERCHES ONT ÉTÉ FAITES
PAR LE CONSEIL NATIONAL DE
RECHERCHES DU CANADA, AINSI QUE
PAR DES UNIVERSITÉS ET DES
GROUPES INDUSTRIELS DE RECHERCHE

of practice, the state of research, and geotechnical engineering education.

History

The history of the beginnings of geotechnical research at Canadian Geotechnical Research Site No. 1 goes back to the early 1950s when it was observed that severe damage and cracking were occurring near the ends of several long dormitory buildings which had been built at the site. A study was authorized using the then recently available principles of soil mechanics, and the study showed that the 1.4 m deep granular fill which had been placed on the poorly drained site to raise the dormitory buildings above existing grade was consolidating the underlying deep compressible clay layers. Substantial total settlements had occurred, of the order of 200 mm, and the damage was caused by differential settlements because the total settlements were much less at the ends of the long narrow loaded strips than in the central zones.

The Division of Building Research of the NRC became interested in this problem site and included it in a long-term program of research on the consolidation of sensitive clays. Other researchers were provided with the NRC results and encouraged to carry out complementary studies. Their valuable results are described in this paper.

It would appear useful to establish at least four broad divisions of geotechnical research at the site. Many projects will include work in more than one division: (*i*) consolidation, (*ii*) strength, (*iii*) deformation, and (*iv*) soil property improvement.

A general outline of the agencies conducting research at the site would be as follows: (*i*) the National Research Council of Canada, (*ii*) universities, and (*iii*) industrial research groups.

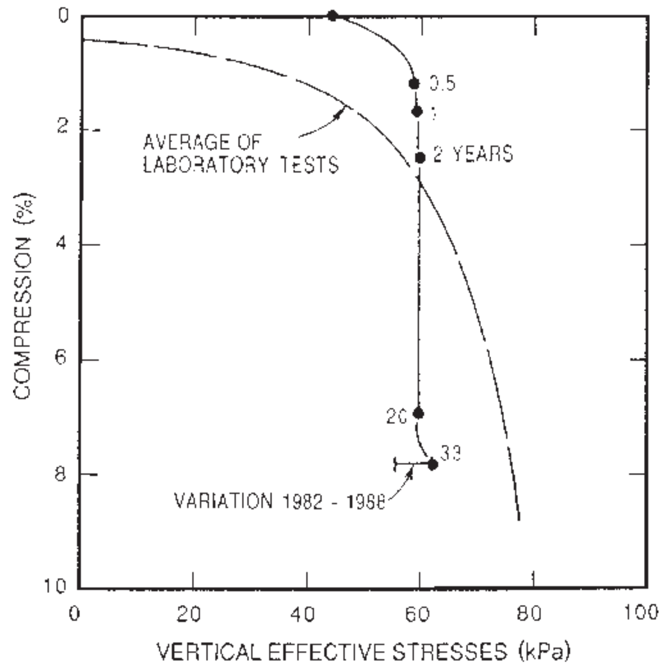
Outline of research activities at the Canadian Geotechnical Research Site No. 1

Consolidation research

CFS Gloucester accommodation building

In 1955, the NRC began settlement observations on a new accommodation building at a Canadian Forces Station, CFS Gloucester, located about 20 km southeast of downtown Ottawa, where the natural clays are only slightly overconsolidated. The total applied pressure of 35 kPa consisted of 33 kPa due to the weight of a sand and gravel pad with a concrete slab surface 1.4 m higher than the original ground surface and only 2 kPa caused by the dead load of a light wood frame building. Details of the construction and the first 20 years of observations are given by Crawford and Burn (1976). After 1 year of loading the effective stresses at the centre of the consolidating layer were at approximately the value of the laboratory measured preconsolidation pressure (σ_p') and the foundation slab had settled about 70 mm. Twenty years later the effective stresses had still not increased further but the slab had settled 300 mm. After 33 years the slab had settled 330 mm and the effective stresses appeared to have increased slightly as shown in Fig. 2 (Crawford and Bozozuk 1990). It was concluded that the consolidation had been almost entirely of a secondary nature because the effective stresses remained constant for so many years. This was attributed to the development of pore pressures by the continuing collapse of the soil structure at the preconsolidation pressure, and this compensated for the influence of natural drainage.

Fig. 2. Consolidation curves at CFS Gloucester accommodation block (after Crawford and Bozozuk 1990).



There have been objections to the term secondary consolidation in the belief that consolidation refers only to the hydrodynamic or primary phase. Forgotten is the simple definition of Terzaghi (1943) that “every process involving a decrease in water content of a saturated soil without replacement of the water by air is called a process of consolidation.”

The American Society for Testing and Materials (ASTM) D653 standard for terminology fortunately follows Terzaghi (1943) by defining (*i*) primary consolidation (primary compression) (primary time effect) as the reduction in volume of a soil mass by the application of a sustained load to the mass and due principally to the squeezing out of water from the void spaces of the mass and accompanied by a transfer of load from the soil water to the soil solids, and (*ii*) secondary consolidation (secondary compression) (secondary time effect) as the reduction in volume of a soil mass caused by the application of a sustained load to the mass and due principally to the adjustment of the internal structure of the soil mass after most of the load has been transferred from the soil water to the soil solids.

Unfortunately the term secondary compression infers that there is a fundamental difference between primary and secondary phases. There is no evidence or reasonable rationale that structural adjustments (secondary consolidation) are not occurring during the hydrodynamic phase. Both primary and secondary consolidation are measures of this structural resistance but during the primary phase the increase in effective stress is delayed by low permeability of the soil. Secondary

Fig. 3. Aerial view of test fill (B) and accommodation building (A) at Gloucester (after Crawford and Bozozuk 1990).

consolidation is a measurable quantity that can be used directly to calculate post-primary settlements in the field. The term compression should be reserved for dimensional changes. Consolidation is therefore a particular kind of compression and, for example, a consolidated–undrained triaxial compression test is precisely described. For an extensive discussion of these matters the reader is referred to Crawford (1964) and subsequent discussions (Altschaeffl 1965; Crawford 1965; Schmertman 1965; Wahls and de Godoy 1965: and Wilson and Lo 1965).

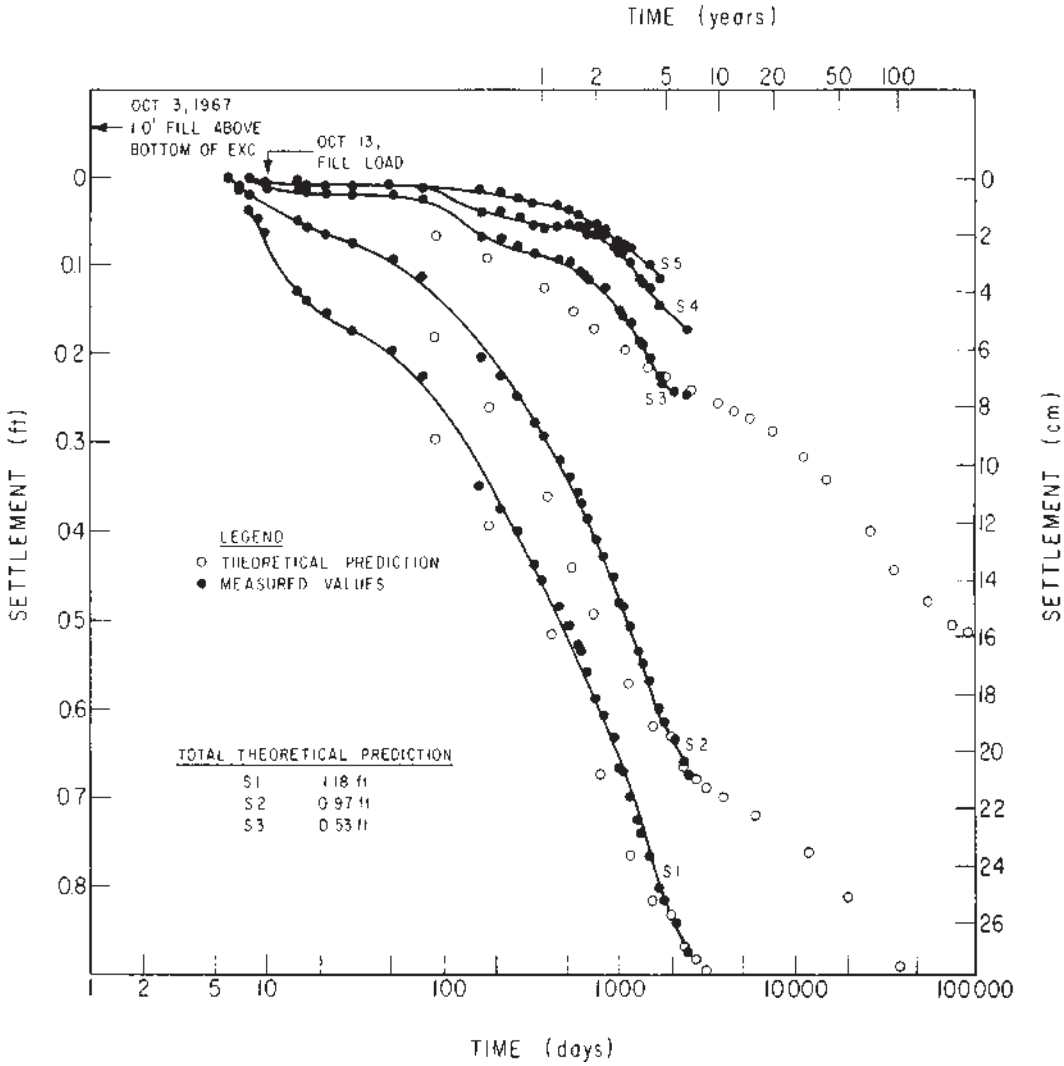
Gloucester test embankment

In 1967, the NRC constructed a well-instrumented research embankment at CFS Gloucester, near the accommodation building described earlier. The embankment (B) and the accommodation building (A) are shown in Fig. 3. The embankment is 9.1 m wide at the top, 36.6 m long, and 3.7 m high, and it was placed in a 1.2 m excavation to reduce the influence of the upper crust on the stresses in the natural soil. The site conditions, laboratory tests, instrumentation, amount and rate of loading, and 4 years of settlement observations were described by Bozozuk and Leonards (1972). All information was made public, and this resulted in cooperative studies and the several very useful publications on laboratory testing and field observations of settlement as described later in the paper.

The Gloucester test embankment was instrumented with earth pressure cells to measure the normal (vertical and horizontal) and shear stresses transmitted to the subsoil. Fifteen settlement gauges were installed just below the embankment and to depths up to 12 m. Twenty piezometers were used to measure pore pressures across the embankment area and to refusal at a depth of about 20 m. Five vertical inclinometers to depths of 10 m provided lateral movement measurements at the side of the embankment and beyond. A horizontal fluid settlement gauge allowed periodic measurements of transverse settlements. Supplementing these measurements were hydraulic fracture tests made using the existing piezometers (Bozozuk 1974). These tests allowed comparisons between values of the coefficient of earth pressure at rest, K_0, measured in the field and in the laboratory.

After 7 years of observations, Lo et al. (1976) reported time–settlement curves and a maximum measured settlement of about 270 mm under the centre of the embankment (Fig. 4). This was approximately equal to a prediction based on the results of long-term laboratory tests and analyzed using the theory of Gibson and Lo (1961). The analysis predicted long-term settlements of about 300 mm after 20 years and 360 mm after 100 years. The observations indicated that primary consolidation was largely completed 1.5 years after the full load of about 54 kPa was applied, and subsequent

Fig. 4. Predicted and observed settlement along centreline of the embankment (after Lo et al. 1976)



settlement was attributed to secondary consolidation. A strange but reproducible behaviour showed that a test specimen resisted deformation at a particular stress level for a period of time and then the structure broke down, resulting in an increased rate of secondary consolidation.

Karstunen et al. (1994) used a number of theoretical methods to determine the contact point between primary and secondary consolidation on the time–settlement curve and finally identified the point at a settlement of 269 mm after 4.3 years of load application. Crawford (1964) contends that "both primary and secondary consolidation are simple empirical divisions of a continuous compression process" and their relative contribution is largely a function of the laboratory test procedure, especially the rate of loading.

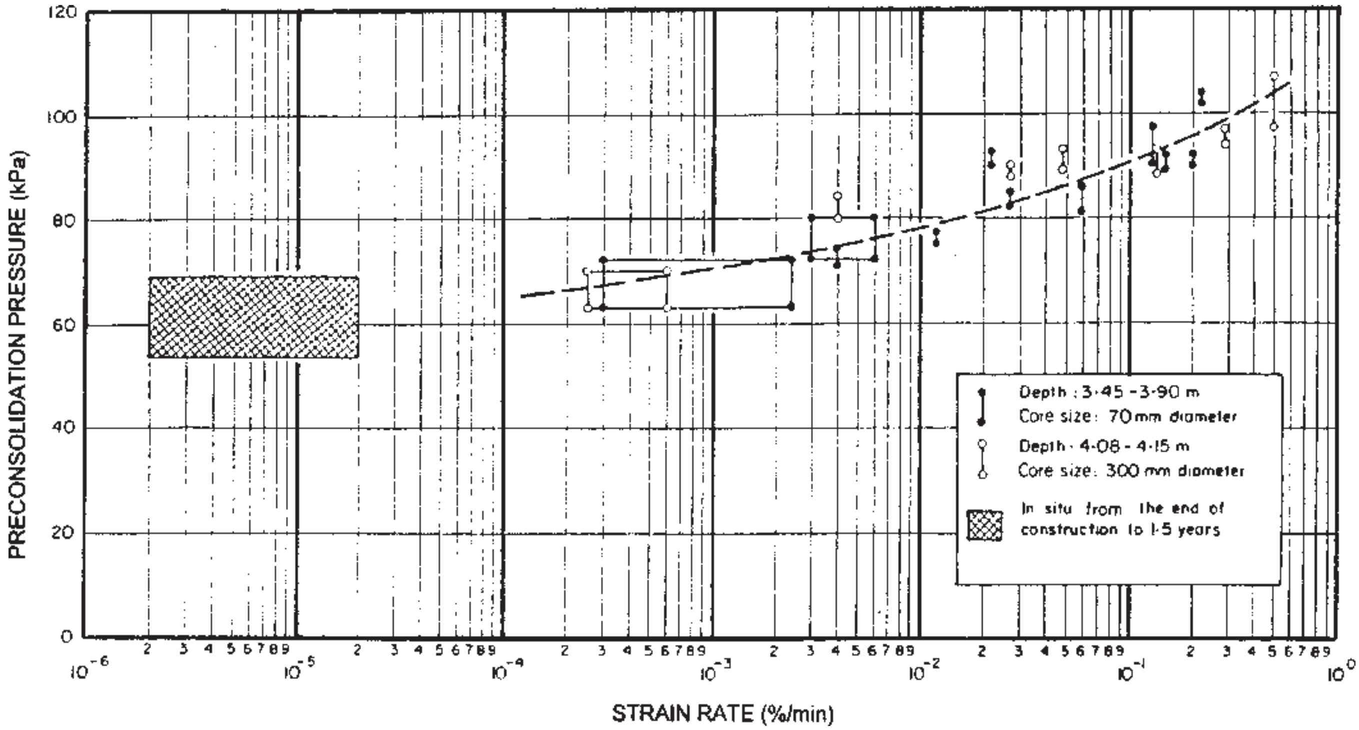
Matyas and Rothenburg (1996) employed several methods to back-analyze the settlement of the Gloucester test embankment. They examined some of the difficulties in applying particular theories to predict the settlement of clays exhibiting high secondary consolidation. They described a procedure based on initial measurements of settlement that could be extrapolated to produce a settlement curve in agreement with the long-term measurements at Gloucester.

Law and Bozozuk (1979) developed a method for estimating excess pore pressures under embankments at the "end of construction" and applied it to the Gloucester test fill. It was found that the calculated excess pore pressures agreed well with measured values under the centreline, but beyond the shoulder they were generally higher than the measured values.

Laboratory consolidation tests

Leroueil et al. (1983*a*) investigated the consolidation properties of samples from 11 sites in the Champlain Sea basin from Gloucester in the west to St-Alban in the east. More than 150 consolidation tests were performed using six test procedures: (*i*) conventional 24 h incremental loading $(MSL)_{24}$, (*ii*) multiple stage load at the end of primary $(MSL)_p$, (*iii*) constant rate of strain (CRS), (*iv*) controlled gradient test (CGT), (*v*) single stage loading (SSL), and (*vi*) anisotropic triaxial consolidation (ATC). Leroueil et al. found that in all cases there was a unique relationship between preconsolidation pressure and strain rate for a given clay at a given depth and that the effect of strain rate on the measured preconsolidation pressure decreases with decreasing strain rate.

Fig. 5. Variation of measured preconsolidation pressure with strain rate in oedometer tests (after Leroueil et al. 1983*b*).



A comparison of test results on samples from several sites using good piston samplers ranging from 50 to 75 mm in diameter and the 200 and 300 mm diameter Laval samplers showed relatively little influence of disturbance. Samples taken with the 200 mm Laval sampler showed less compressibility in the overconsolidated range but no significant difference in the σ_p' values at shallow depths.

The Gloucester site was included in the 11 sites described above, but the results are discussed in more detail in a second paper by Leroueil et al. (1983*b*) and the influence of strain rate is shown in Fig. 5. These results are compared with the estimated range of values (in the cross-hatched area) under an embankment during the first 1.5 years after loading. The averaged curve shows that tests at low strain rates correlate well with in situ measurements of σ_p'.

Complementary work by Morin et al. (1983) at five sites used several methods to determine settlements at depth under full-scale loads for correlation with laboratory measurements of preconsolidation pressures. They concluded that the conventional incremental loading oedometer tests are quite satisfactory for estimating the in situ values of σ_p' for slightly overconsolidated clays (with an overconsolidation ratio, OCR, of 1.2–2.5). They proposed a small correction factor for soils with a lower or higher OCR.

Bozozuk (1971) conducted strength and consolidation tests on a soft sensitive clay obtained at CFS Gloucester using the 54 mm Norwegian piston sampler and the 124 mm Osterberg sampler. Specimens cut from the larger Osterberg sampler gave better $\Delta e - \log \sigma_v'$ curves (where e is the void ratio and σ_v' is the effective overburden pressure) and higher values for the preconsolidation pressures, the average difference being about 16 kPa. Samples from the same site were extruded, waxed, and stored in a humid room for 1.5 years at a temperature of 13°C and a relative humidity ranging from 90 to 100%, and it was found that only about a 5% reduction in σ_p' occurred during storage.

Another comparative study of consolidation testing methods was done by Bauer and El-Hakim (1986), and Demartinecourt et al. (1986) studied a numerical model.

Strength and deformation research

Screw plate tests

The screw plate test is an extension of the plate load test in which a single cycle of a helical auger is inserted into the soil to the desired depth and then loaded axially from the surface. It has been used in cohesive soils for about 25 years to estimate the undrained elastic modulus, E_u, and the undrained shear strength, C_u, of the soil below the plate. Selvadurai et al. (1980) reported the results of screw plate tests at depths of 2 and 4 m near the CFS Gloucester test embankment and compared the results with the values reported by Bozozuk and Leonards (1972) at this site. The agreement appeared to be satisfactory. Later, at the Geotechnical Laboratories at Carleton University in Ottawa, a light-weight helical auger device was developed which could be pulled axially to measure undrained deformability characteristics and shear strength. The pitch, diameter, length, and plate thickness of the auger can be varied depending on the anticipated soil conditions (Selvadurai 1983). The study of borehole shear devices was continued later by Bauer and Demartinecourt (1986), Demartinecourt and Bauer (1986), and Mital and Bauer (1989).

Much research has been devoted to theoretical analyses by Selvadurai and Nicholas (1979) and by Selvadurai (1984). Selvadurai (1984) considered the disturbance from the screw plate to be equivalent to disturbance by the more expensive pressuremeter and similar tests, and Selvadurai and Nicholas

(1979) stressed the need for more field tests for comparison with theoretical calculations.

Field vane tests

Comparative tests using field vanes for strength determination were also done at the Gloucester site (see Law 1985).

Soil improvement research

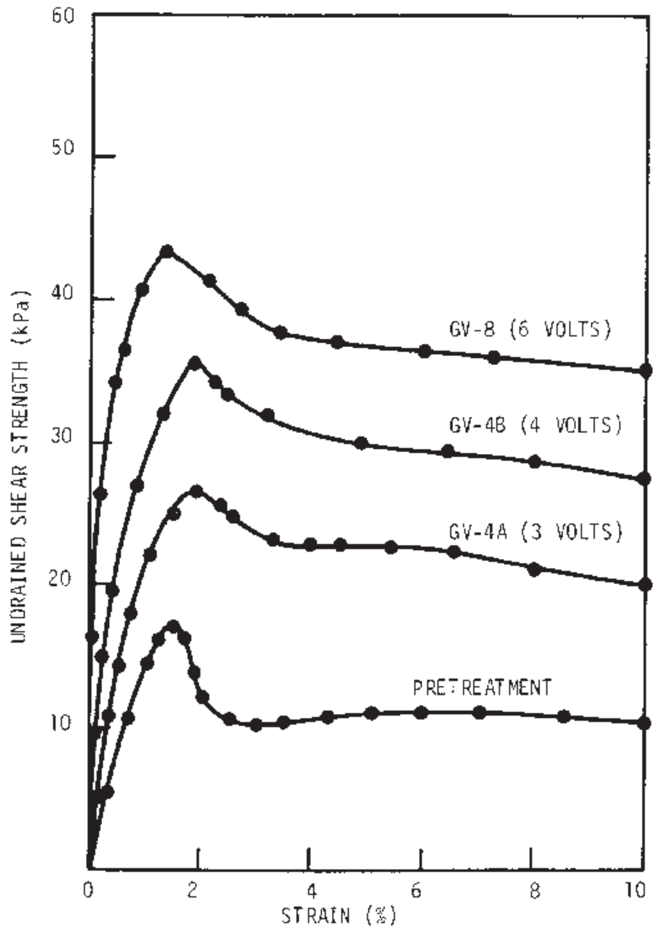
Electroosmotic strengthening

Lo et al. (1991*a*) developed a special electroosmotic cell to minimize voltage losses, prevent gas accumulation, and permit the monitoring of pore pressures and volume changes during laboratory tests. The influence on undrained shear strengths of Gloucester clay after 1.5 days at a potential difference of up to 6 V is illustrated in Fig. 6. The water content decreased by 30%, the shear strength increased by 182%, and the measured preconsolidation pressure increased by 88%.

Lo et al. (1991*b*) followed up their laboratory investigation with a field installation near the Gloucester test fill site to assess the effectiveness of electroosmosis in strengthening the soft Leda clay in situ. Nine electrodes, designed according to previous experience in the laboratory study, were installed to a depth of 5.5 m in a 9.15 m square grid. During treatment the ground settlement, vane shear strength and voltage distribution were monitored with time. The initial applied potential difference of 25 V was regulated periodically to maintain a current of approximately 40 A. It had been found in the laboratory that reversing the current provided more effective treatment, so after 18 days a reversal was made. The electrodes used in the field were similar in design to those used in the laboratory, so water could flow either way. The technique of polar reversal provided a more uniform treatment in the ground. The maximum average vane shear strength after 32 days at a current of 40 A had increased 60% between electrodes spaced at 3 m and 40% at a spacing of 6.1 m. The final settlement of the ground surface was approximately 50 mm.

Lo and Ho (1991) expanded the previous studies at the same Gloucester site by including unconfined compression tests, consolidated undrained triaxial tests, and physicochemical tests of the pore water. Test results confirmed the earlier work and also showed that the treatment had raised considerably the strength envelope in the low effective stress range. The maximum increase in preconsolidation pressure was about 85%. Electroosmosis is also shown to increase the plasticity and reduce the sensitivity of the soil. These research activities have demonstrated the potential value of electroosmosis in improving the properties of the soft sensitive Leda clays that occur in the southern part of the National Capital Region.

Fig. 6. Unconfined compression test of Gloucester clay samples before and after electroosmotic treatment (after Lo et al. 1991*a*).



Future research

This paper provides a key to the literature, but the reader is encouraged to refer to original publications for details.

The authors hope that readers and discussers will add to this admittedly incomplete summary of work that has involved Canadian Geotechnical Research Site No. 1. It is only with such contributions that the purpose of this publication will be fulfilled, namely to create as complete a record as possible and hence assist all future research involving the site.

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