

CHARACTERIZATION BY SAMPLING AND IN SITU TESTING – CONNECTICUT VALLEY VARVED CLAY

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Abstract: Varved clays, which consist of alternating layers of silt and clay, are common in glaciated regions of North America and Northern Europe. This layering results in several unique engineering properties making varved clays a challenging soil for engineering design. Varved clays have hydraulic conductivity and undrained shear strength anisotropy that far exceeds that of most other soils. The strength of the soil for shearing along the horizontal varves is much less than that for shearing across the varves. This paper summarizes the geotechnical engineering properties of Connecticut Valley Varved Clay (CVVC). CVVC is a lacustrine soil deposited approximately 15,000 years ago during retreat of the Laurentide Ice Sheet. Results from soil sampling, in situ testing, and laboratory testing conducted during the past 15 years for a deposit of CVVC at the National Geotechnical Experimentation Site in Amherst, Massachusetts, USA, are presented.

1. INTRODUCTION

Varved clay deposits are common in glaciated regions of North America and Europe north of the 40th parallel and are a prolific source of serious construction difficulties (TERZAGHI et al. [13]). The layered nature of these soils requires special design considerations for geotechnical problems. The strength of the soil for shearing along the horizontal varves is much less than that for shearing across the varves. Because of the silt layers, the horizontal hydraulic conductivity can be far greater than that in the vertical direction. Laboratory testing of varved clays is problematic because results depend greatly on specimen size and the relative portions of the silt and clay layers used for test specimens. Thus directly relating laboratory test results to anticipated field behaviour could be greatly misleading.

In this paper, the geotechnical engineering properties of Connecticut Valley Varved Clay (CVVC) are summarized based on data collected for a test site located in western Massachusetts, USA. The site is on the University of Massachusetts Amherst (UMass Amherst) campus and is a US National Geotechnical Experimentation Site (NGES). Since 1989, the site has been the focus of education and research on soil sampling, in situ testing, groundwater hydraulics, laboratory testing, and prototype and full-scale testing of geotechnical engineering structures. This paper is an abridged version of DEGROOT and LUTENEGGER [4].

2. GEOLOGY

CVVC is a lacustrine soil deposited in Lake Hitchcock during the retreat of the late Pleistocene ice sheet in New England, USA. Glacial Lake Hitchcock started forming approximately 15,000 calendar years ago due to a natural debris barrier at Rocky Hill, Connecticut (figure 1). The Lake expanded along the current Connecticut River Valley and extended northwards approximately 320 kilometers along the Vermont–New Hampshire border to Burke, Vermont. The primary bedrock source materials for CVVC were Triassic rocks in the Connecticut River Valley and distant igneous and metamorphic rocks to the north and east (LADD and WISSA [7]). Deposits were carried into the lake by melt water streams formed during retreat of the Laurentide Ice Sheet. During the summer months the combination of active water conditions in the lake and low cation

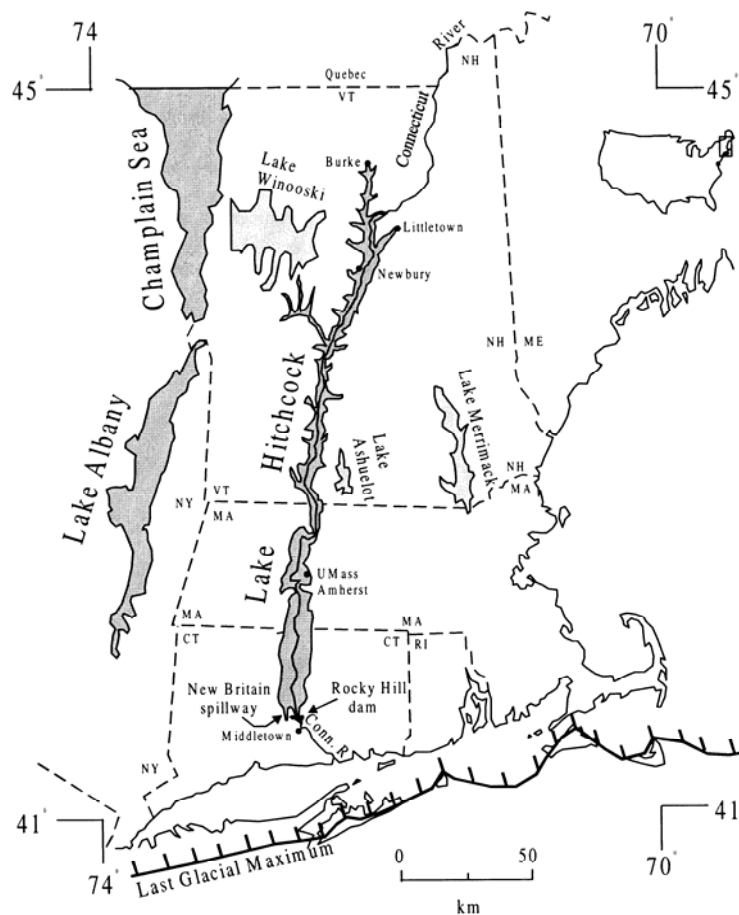


Fig. 1. Location of glacial Lake Hitchcock and UMass Amherst NGES (RITTENOUR [10])

concentration of the cold lake water kept the clay particles in suspension and only the fine sand and silt particles deposited on the lake bottom. However, during the winter months the lake surface froze and the calmer water conditions allowed clay particles to settle to the lake bottom. Thus, each year, two layers of soil deposits formed on the lake bottom. Each couplet of a silt-sand layer and a clay layer constitutes one varve.

CVVC typically rests on top of a relatively thin layer of coarse grained glacial till that covers the underlying bedrock surface. The final thickness of CVVC varies considerably due to large differences in bedrock elevations and variations in post-deposition erosion. In some regions, the deposit is over 50 m thick. The thickness of individual varves ranges from a few millimeters to as thick as 1 m. Close to the ice margin or deltas, large volumes of sediment entering the lake quickly created thick varves, whereas the reduced volume of sediment at locations well away from the ice margin or deltas resulted in thinner varves. The transition from the silt-sand layer to the clay layer is gradual, whereas the transition from the clay layer to the silt-sand layer is abrupt. Typically, most of the variation in thickness of the varves is in the summer silt-sand layer, whereas the winter clay layer changes relatively little in thickness.

The UMass Amherst NGES is located 1.5 km east from the old shore of glacial Lake Hitchcock (figure 1), which was approximately 20 km wide in the area. The stable lake elevation was at 90 m above sea level with a water depth at the site of about 77 m at the start of CVVC deposition (RITTENOUR [10]). A 33 m long core of CVVC from ground surface to bedrock was collected at the UMass Amherst NGES using a 100 mm diameter central mining equipment continuous sampler. Material from the bottom of the core was deposited immediately after deglaciation approximately 15,400 calendar years before present (= 12,800 ^{14}C BP; RITTENOUR and BRIGHAM-GRETTE [11]), while the material at the top of the core was deposited about 1,000 years after the ice had retreated from the Amherst area. Overall, the continuous profile revealed that at this site the deposit contains 1,389 varves (RITTENOUR [10]).

Approximately 14,000 calendar years before present, the barrier dam at Rocky Hill, Connecticut, was breached and Lake Hitchcock started to drain. When the water level dropped to the lake bottom near the southern region of the lake, the Connecticut River formed. In some regions, especially in the flood plains, extensive erosion took place during drainage of the lake. It is, however, unknown how much, if any, erosion occurred at the UMass Amherst NGES. After drainage, the surface sediments were exposed to an arid and cold climate.

It is clear from visual inspection of samples and consolidation data that the upper few meters of the deposit have undergone significant changes as a result of desiccation, freeze/thaw cycles, possible permafrost conditions after drainage, and other weathering. This zone, commonly known as a crust, extends to about 5 to 6 m below ground surface. The crust soil is typically brown and therefore oxidized as compared

to the predominately reddish (local Triassic source) or gray colored (distant crystalline source), unoxidized CVVC below the crust.

Currently, the ground water table at the NGES typically occurs in the upper 2 m below ground surface and varies as much as approximately 2 m throughout the year coinciding with changes in seasonal precipitation. There is a slight artesian pressure deep in the deposit which is consistent with the local topography, since the site is situated in a valley and the lower granular glacial till is contiguous throughout the valley and is exposed in the nearby hills.

3. CLASSIFICATION AND INDEX PROPERTIES

There are significant differences in properties between the clay and silt layers. Thus classification and index data, such as water content and Atterberg limits, depend on the proportions of silt and clay layers in a test specimen. Most of the data presented here are of bulk properties. Inevitably some portion of the scatter in the bulk properties will be due to varying amounts of silt and clay in an individual specimen.

Within a varve, the water content typically is a minimum value at the bottom of a varve and gradually increases with increasing elevation as the soil becomes finer grained and more plastic. It then abruptly changes back to the minimum coinciding with the transition from the winter to the summer season. As a result, the water content can vary as much as 40% from the bottom to the top of a varve. Natural water content and void ratio for the bulk soil is typically lowest near the ground surface due to desiccation and seasonal changes in the water table as shown in table 1 and figure 2. The total density data follow an inverse pattern of the water content data with the highest values in the crust ($\rho_t = 1.92 \text{ Mg/m}^3$) and the lowest values below the crust ($\rho_t = 1.66 \text{ Mg/m}^3$). The density of solids for the soil is uniform throughout the deposit with $\rho_s = 2.88 \text{ Mg/m}^3$ for the bulk soil, $\rho_s = 2.87 \text{ Mg/m}^3$ for the silt layers, and $\rho_s = 2.91 \text{ Mg/m}^3$ for the clay layers.

Grain size data from hydrometer analyses of the bulk soil at the UMass Amherst NGES gives a clay fraction (% < 0.002 mm) of approximately 65% and a silt fraction (% between 0.002 mm and 0.075 mm) of 35% (table 1 and figure 2). Occasionally, a small sand fraction is found in samples. Individual clay layers have a clay fraction in excess of 80% and individual silt layers have a silt fraction in excess of 80%. LADD [5] reports that the clay layers of CVVC consist mostly of illite and chlorite with some quartz, and the silt-sand layers consist largely of quartz and feldspar with some micaceous minerals.

Atterberg limits data for bulk samples of CVVC plot on a Casagrande plasticity chart around the A-line. Atterberg limits for individual clay layers have the same plastic limit as the bulk soil but a higher liquid limit and typically plot above the

A-line with a corresponding Unified Soil Classification System (USCS) classification of CH. The silt layers have a much lower liquid limit and typically plot below and above the A-line with a USCS of ML or CL.

Table 1

Typical average UMass Amherst NGES CVVC index properties with depth (after DEGROOT and LUTENEGGER [4])

Depth (m)	Sand (%)	Silt (%)	Clay (%)	Density ρ_t (Mg/m ³)	w (%)	LL (%)	PL (%)	PI (%)	LI (-)	A (-)
0.0–1.4	–	–	–	1.92	24	–	–	–	–	–
1.4–3.1	2	62	36	1.89	37	39	28	11	0–1	0.31
3.1–6.1	1	47	52	1.73	52	51	31	20	1.1	0.38
6.1–24.0	0	45	55	1.66	62	51	30	21	1.5	0.38
Clay	0	17	83	–	–	65	30	35	–	0.42
Silt	1	72	27	–	–	38	28	10	–	0.37

LL = liquid limit, PL = plastic limit, PI = plasticity index, LI = liquidity index, A = activity (PI/% < 0.002 mm).

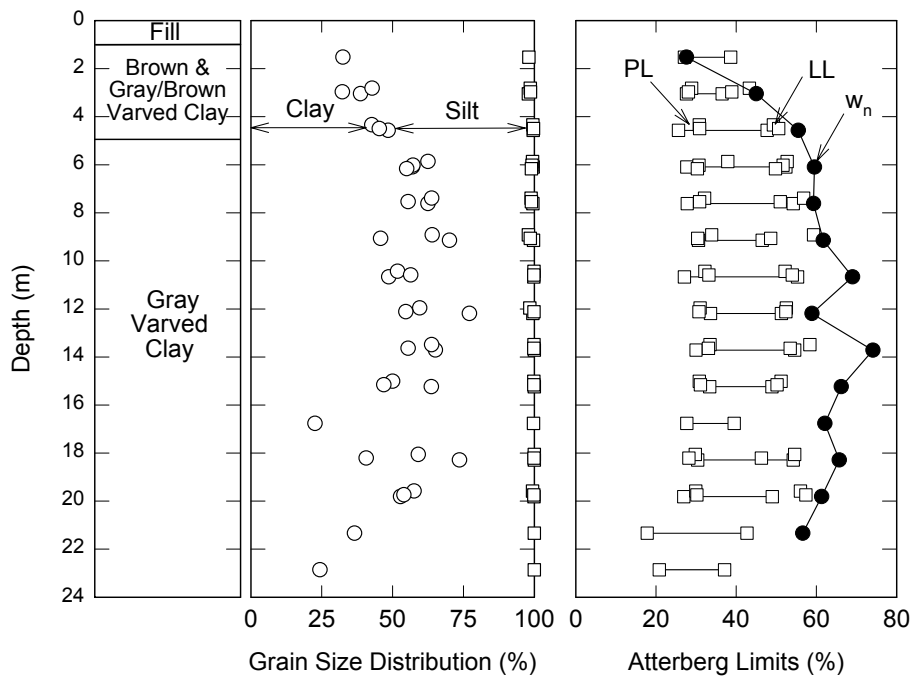


Fig. 2. UMass Amherst NGES soil profile: bulk soil grain size distribution and Atterberg limits (DEGROOT and LUTENEGGER [4])

4. HYDRAULIC CONDUCTIVITY

Hydraulic conductivity (k) of CVVC is dominated by the layering of the soil. Flow in the vertical direction (perpendicular to the varves) is largely controlled by the lower permeability clay layers, whereas flow in the horizontal direction is largely controlled by the more permeable silt layers and occasional sand lenses. Figure 3 plots hydraulic conductivity data based on several in situ and laboratory measurements. In situ measurements were made by conducting slug tests in open standpipe piezometers and dissipation tests using a $10 \text{ cm}^2 u_2$ CPTU (DEGROOT and LUTENEGGER [3]). Laboratory tests were conducted on 76 mm fixed piston samples and a few block samples using a flexible wall permeameter. Specimens were backpressure

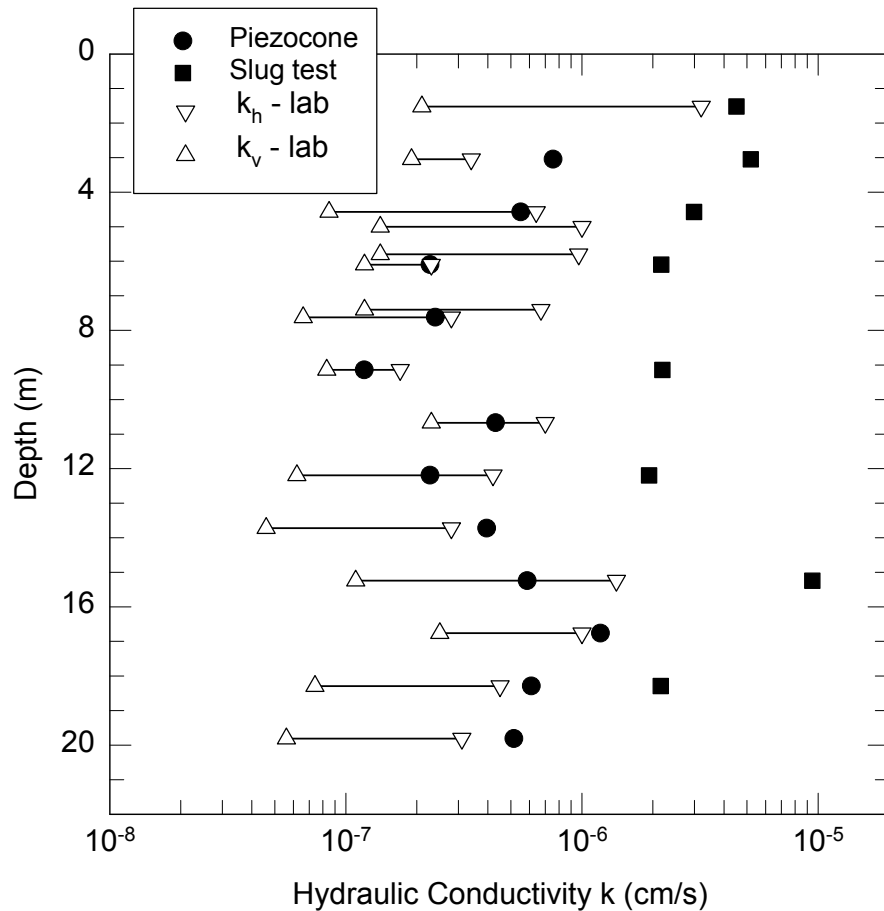


Fig. 3. UMass Amherst NGES CVVC vertical and horizontal hydraulic conductivity from in situ and laboratory tests (DEGROOT and LUTENEGGER [4])

saturated and isotropically consolidated to the in situ vertical effective stress. Companion specimens were trimmed and oriented for flow perpendicular (k_v) and parallel (k_h) to the direction of the varves.

The laboratory values of k_v and k_h show near parallel plots versus depth. The anisotropy ratio $r_k = k_h/k_v$ ranges between 2 to 14 and averages approximately 6. These tests are, however, on relatively small specimens. Slug tests conducted in the open standpipe piezometers give much higher values with k_h ranging from about 2×10^{-6} cm/s to 1×10^{-5} cm/s (figure 3). These data and the laboratory flexible wall results for flow parallel to the varves give a ratio of in situ to laboratory k_h equal to approximately 7. Whereas the in situ data and the laboratory data for flow perpendicular to the varves (k_v) imply a r_k ranging from 20 to 80 with a majority of the data between 20 and 30. These data suggest that r_k of individual varves is probably in the order of 5 to 10, whereas r_k of the in situ soil over a large scale is much higher and averages approximately 30.

The CPTU interpreted data show trends with depth similar to the laboratory and slug test data but with different values. The CPTU data are similar to these of laboratory k_h values and much lower than the in situ slug test values. It is evident that the CPTU values are influenced by several factors as compared to the slug test method: varve smearing and remolding during penetration, scale effects, and uncertainties in the interpretation method.

5. PRECONSOLIDATION STRESS

The stress history of CVVC can vary significantly, depending on site-specific geologic history. In most cases, however, the soil is generally overconsolidated at shallow depths (i.e. "crust") due to one or more mechanisms such as erosion, fluctuating water table, desiccation, cementation, oxidation/reduction, and freeze-thaw. At greater depths the soil is typically lightly overconsolidated. At these depths, some of the possible mechanisms are the effects of surface erosion, cementation and aging. Figure 4 plots stress history data as determined from the results of IL and constant rate of strain (CRS) consolidation tests on tube and block samples. The volumetric strain (ε_{vol}) values plotted in figure 4a correspond to the laboratory recompression strain to σ'_{v0} as measured in the consolidation tests.

Estimates of the preconsolidation stress σ'_p were made using a combination of Casagrande construction and the strain energy method (BECKER et al. [1]). The ε_{vol} at σ'_{v0} data were used to assess the sample quality using the Specimen Quality Designation (SQD) method of TERZAGHI et al. [13]. In this method, specimens of A ($\varepsilon_{vol} < 1\%$) and B ($1\% < \varepsilon_{vol} < 2\%$) quality are considered reliable for σ'_p estimates, specimens of C ($2\% < \varepsilon_{vol} < 4\%$) quality are possibly reliable, and specimens of D

($4\% < \varepsilon_{vol} < 8\%$) and E ($\varepsilon_{vol} > 8\%$) quality are unreliable. Independent of the SQD data, it is apparent from the data in figure 4b that many of the deep piston samples are from fair to poor quality based primarily on estimated σ'_p values that are less than σ'_{v0} .

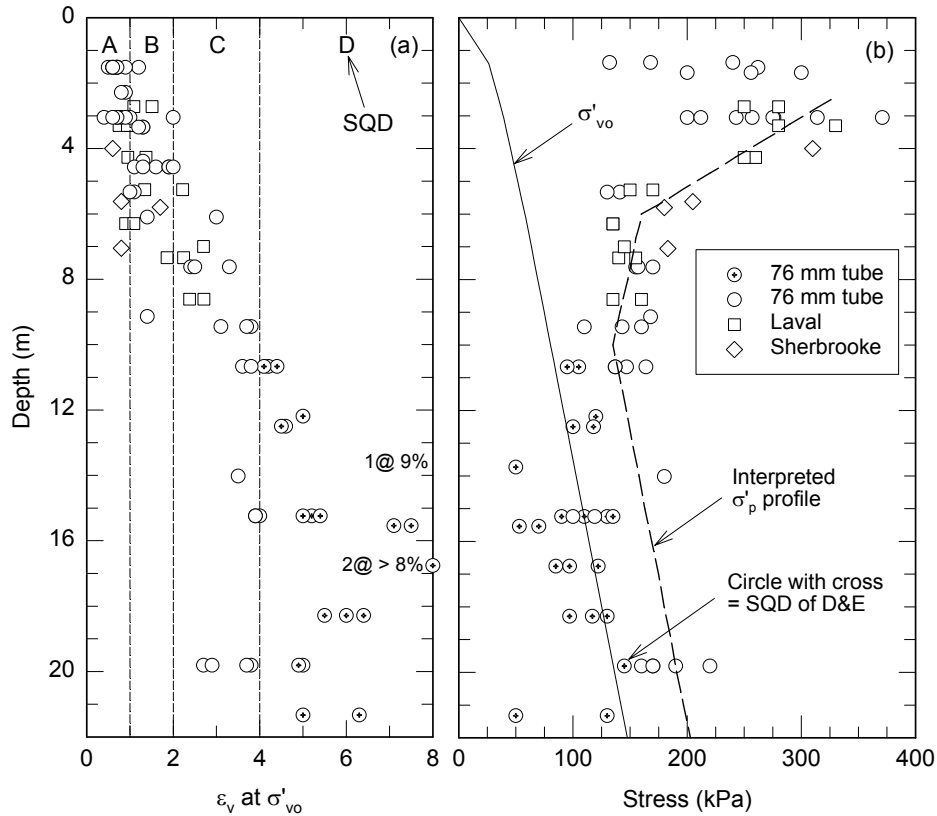


Fig. 4. UMass Amherst NGES CVVC stress history data: a) SQD; b) in situ vertical effective stress and preconsolidation stress (DEGROOT and LUTENEGGER [4])

The data in figure 4 clearly show evidence of the stiff crust in the upper five meters followed by soil of a low overconsolidation ratio (OCR) throughout the remainder of the deposit. There are significant variations in estimates of σ'_p in the crust in spite of the fact that most of these tests were conducted using the same methods. This is to be expected in most clay crusts because of local variations in stress history mechanisms such as desiccation, etc. For the “interpreted stress history” line fitted to the data in figure 4, which discounted the D and E quality samples, the OCR ranges from 9.3 at 2.5 m to 1.4 at a depth of 20 m.

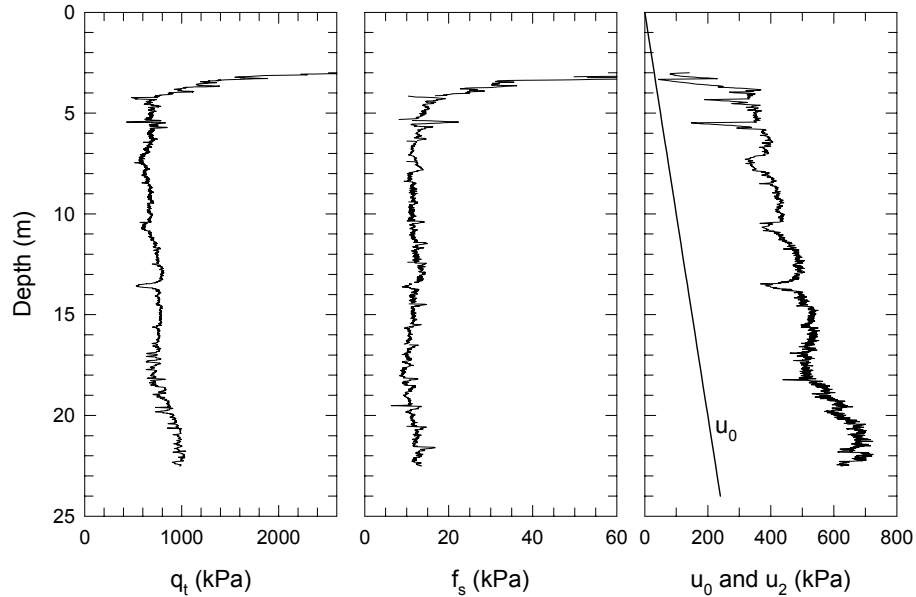

 Fig. 5. UMass Amherst NGES CVVC CPTU- u_2 profile

Figure 5 plots measured data from a Piezocone (CPTU) profile conducted using a 10 cm^2 cone with pore pressure behind the cone shoulder u_2 . All measured parameters clearly indicate the location of the upper crust and the transition to the softer CVVC below 5 m. The corrected cone resistance q_t ($q_t = q_c + (1 - a)u_2$, where q_c stands for the measured tip resistance, and a is the net area ratio) increases slightly with depth below the crust with values ranging between 600 to 1000 kPa. The stress history data of figure 4 together with the CPTU data of figure 5 can be used to back calculate the correlation for determining σ'_p from CPTU data as $\sigma'_p = \alpha_t(q_t - \sigma_{v,0})$. The α_t values vary significantly in the crust, but for the data below the crust (6 m) they range from approximately 0.25 to 0.40 with an average value equal to 0.30. This value compares favourably with that found for other low plasticity clays (e.g., see LUNNE et al. [8]).

6. COEFFICIENT OF LATERAL EARTH PRESSURE AT REST

Self-Boring Pressuremeter (SBPM) tests were conducted at the site using a modified Cambridge SBPM that has nine strain arms set at three levels in the probe (BENOIT and LUTENEGGER [2]). Figure 6 plots the data based on the average curves for each tier of strain arms and converted to coefficient of lateral earth pressure at rest (K_0) values. In figure 6, there are also plotted data from the DMT using the Marchetti

correlation [9] and from spade cells. There is considerable scatter in the data although some trends are evident. The values of K_0 are very high in the crust, approaching values of 2.5, and rapidly decrease to values below 1.0 at 10 m and then decrease much more gradually below 10 m.

Laboratory measurements of K_0 were conducted using an instrumented oedometer ring with strain gages for measurement of lateral stress during IL consolidation. Tests were conducted by first incrementally loading past σ'_p to measure K_0 for laboratory OCR = 1 and then using incremental unloading to measure K_0 versus OCR for simple mechanical unloading. For the unloading data between OCR equal to 1 and 8 the data are well represented by

$$K_0 = 0.60(\text{OCR})^{0.41}. \quad (1)$$

This relationship is plotted in figure 6 for depths below the crust using the interpreted stress history profile of figure 4 which predicts a $K_0 = 0.69$ at 20 m below ground surface for the interpreted OCR of 1.4 at that depth. It is, however, clear that the relationship of equation (1), based on mechanical stress history only, does not predict the measured SBPMT and spade cell data well for the upper section of the deposit.

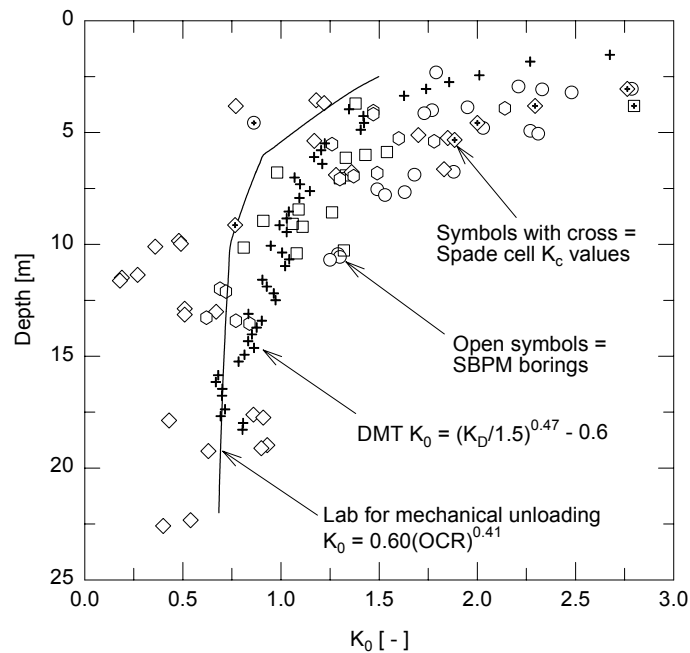


Fig. 6. UMass Amherst NGES CVVC coefficient of lateral earth pressure at rest from in situ tests and laboratory measurements (DEGROOT and LUTENEGGER [4])

7. SHEAR STRENGTH

Field vane tests (FVT) were conducted using a Nilcon Vane Borer with a 130 mm × 65 mm vane with 1.9 mm thick rectangular blades. The remoulded vane strengths were determined after 10 full revolutions of the vane were conducted. Figure 7 plots the average FVT peak values of undrained shear strengths s_u from several profiles. These data show very high strengths in the crust with a rapid decrease towards the bottom of the crust at approximately 6 m. Thereafter s_u is approximately constant with depth with most values ranging between 30 and 40 kPa. Below a depth of 6 m, the data averages are $s_u = 35$ kPa and $s_{ur} = 4$ kPa, giving a sensitivity S_t based on these average values equal to 9, although individual S_t values vary significantly between 5 and 25. For reference the interpreted DMT data using the MARCHETTI [9] correlation for s_u are also plotted in figure 7.

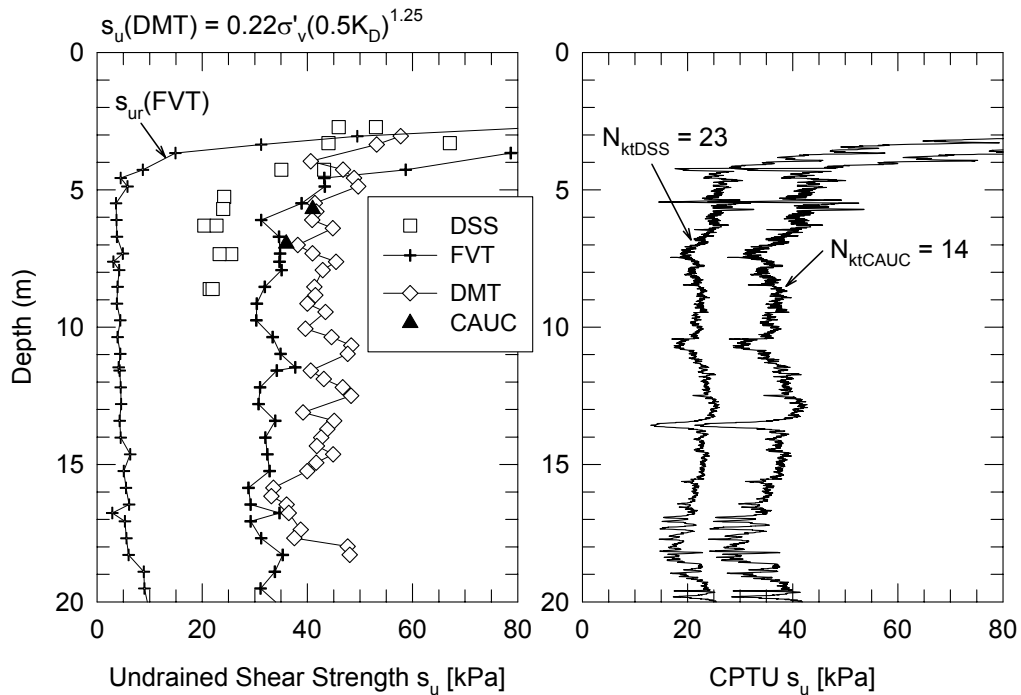


Fig. 7. UMass Amherst NGES CVVC undrained shear strength data from laboratory recompression tests (DSS, CAUC) and in situ tests (FVT, DMT, and CPTU)

Recompression (i.e. $\sigma'_{vc}(\text{lab}) = \sigma'_{v0}$) undrained direct simple shear (DSS) tests and anisotropically consolidated undrained triaxial compression (CAUC) tests were conducted on Laval and Sherbrooke block samples. The $s_u(\text{DSS})$ data when combined

with the corresponding σ'_p values from the same block samples (see figure 4) give the following relationship between normalized undrained shear strength and OCR

$$s_u(\text{DSS})/\sigma'_{vc} = 0.15(\text{OCR})^{1.0}. \quad (2)$$

The CAUC test gave s_u values greater than that measured in the DSS test with an anisotropy ratio for corresponding test pairs averaging

$$K_s = s_u(\text{DSS})/s_u(\text{CAUC}) = 0.63. \quad (3)$$

Table 2 summarizes results for a number of SHANSEP (LADD [6]) tests conducted on CVVC samples loaded to an OCR = 1 state of stress in the laboratory. There are also included some results reported by SAMBHANDHARAKSA [12] for samples of CVVC primarily taken from a site close to the UMass Amherst NGES. The anisotropy ratio for the CK_0U triaxial data is

$$K_s = s_u(CK_0UE)/s_u(CK_0UC) = 0.84, \quad (4)$$

while considering DSS mode of shear relative to CK_0U triaxial compression is

$$K_s = s_u(\text{DSS})/s_u(CK_0UC) = 0.72. \quad (5)$$

It is clear that CVVC exhibits significant undrained shear strength anisotropy like most low plasticity clays, but unique to CVVC is the fact that the DSS mode of shear gives lower s_u values than the TE mode of shear. In most sedimentary clays, the opposite is the case.

Table 2

UMass Amherst NGES CVVC undrained shear strength data for OCR = 1 SHANSEP tests
(after DEGROOT and LUTENEGGER [4])

Shear mode	s_u/σ'_{vc} (-)	ε_f (%)	A_f (-)	ϕ' (°)
CIUC	0.24	3.8	1.4	25
CAUC	0.25	1.0	1.7	22
CK_0UC^1	0.25	0.8	1.3	21
CK_0UE^1	0.21	9.4	1.1	33
DSS	0.18	-	-	-
CDDS	-	-	-	24

¹ Data from SAMBHANDHARAKSA [12]; all triaxial data for q_f ; A_f equals Skempton's pore pressure parameter at q_f .

The data in table 2 show the high shear induced pore pressures generated in CVVC for compression modes of shear (Skempton pore pressure parameter at peak q , $A_f > 1$) and relatively low friction angle based on failure envelopes plotted through the peak shear strength q_f . Consolidated drained direct shear box (CDDS) tests conducted on

specimens from below the crust give a failure envelope with $\phi' = 24^\circ$ and near zero cohesion intercept.

The DSS, CAUC, and FVT data of figure 7 together with the CPTU data of figure 5 can be used to back calculate the correlation factor for determining s_u from CPTU data using $s_u = (q_t - \sigma_{v0})/N_{kt}$. The resulting N_{kt} values are erratic within the crust, whereas the values for below the crust are much more uniform. Average values below the crust corresponding to each test type are $N_{ktDSS} = 23$, $N_{ktCAUC} = 14$, and $N_{ktFVT} = 16$. These values are at the high end of typical values reported in the literature (e.g. LUNNE et al. [8]), particularly the N_{ktDSS} value, which reflects the relatively weak undrained shear strength of CVVC for shearing parallel to the varves. Figure 7 plots the interpreted CPTU profiles for N_{ktDSS} and N_{ktCAUC} .

8. SUMMARY

The unique properties of varved clays make them a challenging soil for geotechnical engineers. Their distinct silt and clay layering gives them flow and strength anisotropy properties that far exceed most other soils. The varved clay deposit at the University of Massachusetts Amherst National Geotechnical Experimentation Site, known as Connecticut Valley Varved Clay (CVVC), has been studied during the past decade through a combination of in situ and laboratory testing. This lacustrine soil was deposited approximately 15,000 years before present and is about 33 m thick at the test site. The deposit has a very distinct crust down to 5–6 m depth that is reflected in almost all in situ, index, and laboratory engineering tests. Below the crust, CVVC is a soft to medium consistency, low over-consolidation ratio soil, with undrained shear strength values in the range from 20 to 35 kPa, depending on test type, and a drained friction angle in the low 20s. However, of greater significance for design, is that CVVC has very unique undrained shear strength anisotropy; the direct simple shear mode of shear (i.e. shear along the varves) gives a much lower undrained shear strength as compared to not only the triaxial compression mode of shear but also to the triaxial extension mode of shear (i.e. shear across the varves). The drainage properties of CVVC are also very unique. The hydraulic conductivity anisotropy of individual varves is generally in the order of 5–10, whereas over the larger scale of the bulk in situ soil, it is much higher and can approach values in the range from 30 to 80. These conditions are rarely encountered in most sedimentary soils and reliable design of structures that involve portions of failure surfaces that run parallel to the varves and involve horizontal drainage must consider these issues.

ACKNOWLEDGEMENTS

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