

Comparison of Field Vane Results with Other In-Situ Test Results

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ABSTRACT: Undrained shear strength results from field vane shear tests are compared with those obtained from flat plate dilatometer, screw plate, pressuremeter, and piezocone tests at several sites in the lower mainland near Vancouver, British Columbia, Canada. The sites include deltaic deposits of soft organic soils, clay silts, and moderately to highly sensitive clays. The sites consist primarily of normally consolidated soils, but results in overconsolidated soils are also included. The test procedures and methods of interpretation are briefly described for each in-situ test type in addition to a discussion of the results.

KEY WORDS: vane, in-situ, field, strength, comparison, dilatometers, screw-plate, pressuremeters, cone penetration tests (CPT), piezocone tests (CPTU)

In recent years there has been a growing tendency towards the use of in-situ testing techniques for evaluating engineering soil parameters. Wroth [1] attributes this growth to the rapid increase in the variety and quality of in-situ testing instruments in addition to our better understanding of the real behavior of soils and the subsequent realization of some of the limitations and inadequacies of conventional laboratory testing. The high cost of offshore geotechnical investigations and the difficulties associated with the recovery of undisturbed samples have made the use of in-situ testing techniques particularly attractive if not essential.

The soil property most often measured in the field in clay soils is undrained shear strength S_u [1,2]. Unfortunately, S_u is not a unique parameter as it depends significantly on the type of test used, the rate of strain, and the orientation of the failure planes [3]. There are several methods available for measuring the undrained shear strength of clay in-situ. Campanella and Robertson [4] presented a table listing various in-situ test methods and their perceived applicability in determining soil parameters. A list of the methods relevant to the measurement of S_u is reproduced in Table 1. Of the 15 in-situ test methods only 2 methods have a rating of high applicability: the field vane shear test (FVST) and the self-boring pressuremeter test (SBPM). Their high rating is a result of their ability to provide a direct evaluation of S_u . Eight entries have a rating of moderate applicability, all of which estimate the undrained shear strength by empirical or semi-empirical methods. Among these are the flat plate dilatometer test (DMT), the screw plate test (SPLT), the cone penetration test (CPT), and the piezocone test (CPTU).

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TABLE 1—Perceived applicability of in-situ test methods to determine undrained shear strength of clays [4].

In-Situ Test Method	Rating
Dynamic cone	C
Static cone	
mechanical cone	B
electrical friction cone	B
electrical piezo cone	B
electrical piezo/friction cone	B
Acoustic probe	C
Dilatometer	B
Field vane shear	A
Standard penetration test	C
Resistivity probe	C
Screw plate	B
Impact cone	C
Borehole shear	B
Menard pressuremeter	B
Self-boring pressuremeter	A

NOTE: A = high applicability. B = moderate applicability. C = limited applicability.

Because it has been proven to be a reliable and highly repeatable test method, the FVST is currently the most common method of measuring S_u in-situ. One of its main advantages is the great deal of experience that has been developed over its long history. However, it does suffer some serious disadvantages. The FVST is incremental with tests usually being conducted at 1-m intervals. The soil type in which the test has been performed must be uniform or homogeneous, and the type is estimated from the test results or confirmed by an adjacent borehole. Verticality of the instrument and profile are not ensured or measured. To prevent damage to the vane blades, preboring is often required through coarse grained material. For these reasons it is often desired to estimate S_u from other in-situ testing methods.

This paper presents a comparison of S_u values determined from various in-situ test methods with field vane shear test results at several of the University of British Columbia (UBC) research sites.

Field Tests

Test Sites

Field tests were conducted at five sites in the lower mainland region of southwestern British Columbia near Vancouver, Canada. In this paper the sites are referred to as McDonald Farm, Cloverdale, Langley Railway, and Upper and Lower 232nd St. sites. They were selected because of the different material properties such as sensitivity and stress history found at each site. Their locations are shown in Fig. 1. A summary of the material properties of the five sites is presented in Table 2.

McDonald Farm

McDonald Farm is a relatively flat lying area located at the northern edge of Sea Island on Ministry of Transport Land adjacent to Vancouver International Airport, several 100

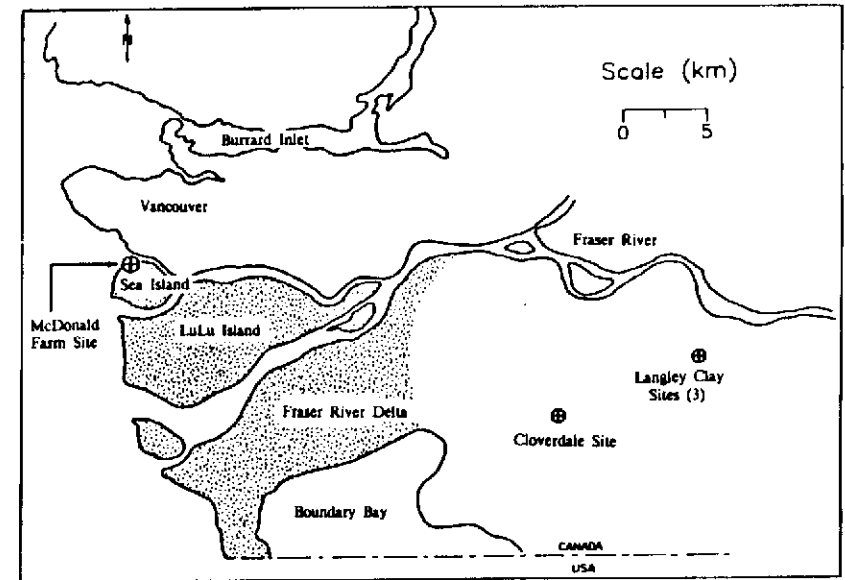


FIG. 1—General location of the UBC research sites.

m south of the north arm of the Fraser River. The island is one of several that make up the Fraser River Delta. The general geology consists of deltaic distributary channel fill and overbank deposits, which overlie post glacial estuarine and marine sediments [5]. A typical soil profile, shown in Fig. 2, indicates that the stratigraphy consists of a 2-m surface layer of soft organic silty clay overlying 11 m of loose to dense medium to coarse sand with some layers of fine sand. These deposits are underlain by a 2-m transition zone of fine sand and silt followed by a thick (up to 300 m) unit of soft normally consolidated clayey silt. This paper will be concerned only with the clayey silt below 15 m.

Cloverdale Site

The Cloverdale site is located adjacent to the Pacific Highway overpass in Cloverdale, British Columbia, and consists of the Cloverdale sediments. These deposits were laid down in a marine proglacial environment when the land was depressed because of the advancement of the Sumas ice [5]. The site is located on level ground approximately 2.3-m above sea level with a stratigraphy consisting of a 2-m surficial fill of wood chips and gravel over 3 m of sensitive organic clay and silt. Below this is approximately 22 m of medium soft sensitive clays and silty clays interbedded with occasional sand lenses. The material between 5 and 16 m is lightly overconsolidated. The high sensitivity of the Cloverdale clay is probably due to leaching after isostatic rebound of the area. A typical soil profile is shown in Fig. 3.

Langley Railway Site

The Langley railway site is located at the base of a 5-m cut adjacent to the Trans Canada Highway. It is approximately 100 m west of the British Columbia Hydro railway overpass near the 232nd St. exit in Langley, British Columbia. The site is located at the eastern

TABLE 2—Summary of material properties at the UBC research sites.

Site	SG	w_l		w_p		w_n		P_l		S_l	
		Range	Avg	Range	Avg	Range	Avg	Range	Avg	Range	Avg
McDonald farm	2.8	25 to 42	35	22 to 25	24	23 to 40	34	3 to 20	15	2 to 7	5
Cloverdale site	2.8	.. .	51	.. .	24	.. .	51	.. .	27	8 to 29	17
Langley railway site	2.8	32 to 59	42	16 to 27	21	.27 to .53	45	16 to 34	24	7 to 10	9
232nd St. sites	2.8	.. .	40	.. .	20	.. .	45	.. .	19	2 to 19	11

NOTE: SG = specific gravity; w_l = liquid limit; P_l = plasticity index; w_n = natural water content; w_p = plastic limit; S_l = sensitivity (field vane).

extent of the Capilano sediments, which consist of raised deltas, intertidal and beach deposits, and glaciomarine sediments [5]. The site profile in Fig. 4 shows that the stratigraphy consists of a 2.5-m surface layer of mixed gravel and sand fill overlying a 7.5-m-thick layer of lightly overconsolidated silty clay with occasional silty sand layers. This in turn is underlain by a deposit of normally consolidated silty clay with occasional silty sand layers. A continuous sample (to 15 m) obtained at the site [6] indicates that the sand content tends to increase with depth.

232nd St. Site

This site is located at the 232nd St. exit of the Trans Canada Highway in Langley, British Columbia, approximately 1 km east of the Langley railway site. The site lies at the western extent of the Fort Langley Formation. This formation has recorded at least three advances and retreats of a valley glacier and consists of interbedded marine, glaciomarine, and glacial sediments [5].

Upper Site—The upper site is situated on a compacted clay fill that forms the approach for the 232nd St. overpass. A profile of the upper site is shown in Fig. 5. The stratigraphy consists of 2.5 m of compacted organic clay fill over a 5-m layer of overconsolidated silty clay, which is underlain by a thick layer of normally consolidated silty clay with occasional sand lenses. Sand content tends to increase with depth.

Lower Site—The lower site is situated slightly above highway level and about 5 m below the elevation of the upper site. The near surface material is overconsolidated because of dessication. A typical profile is shown in Fig. 6.

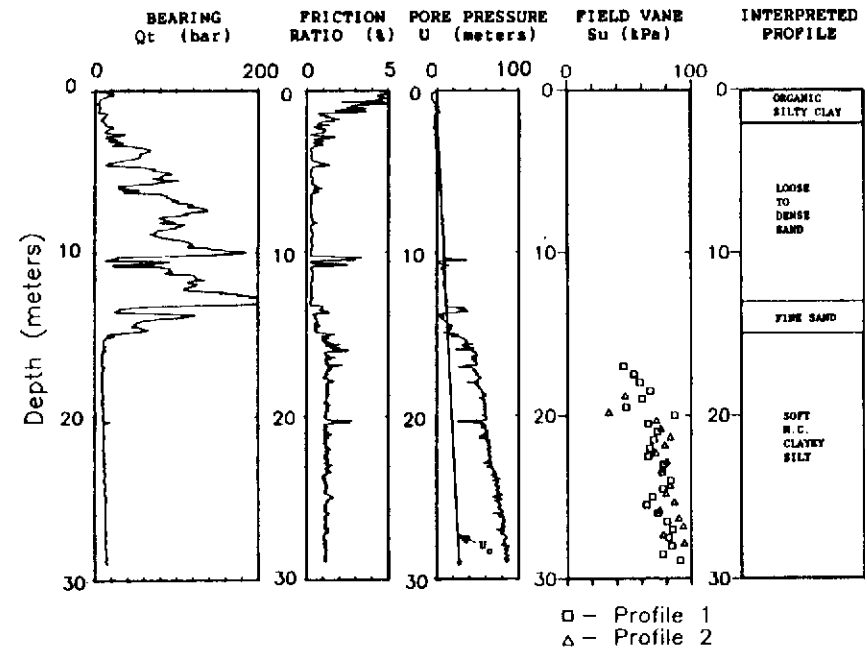


FIG. 2—Soil profile at the McDonald Farm site.

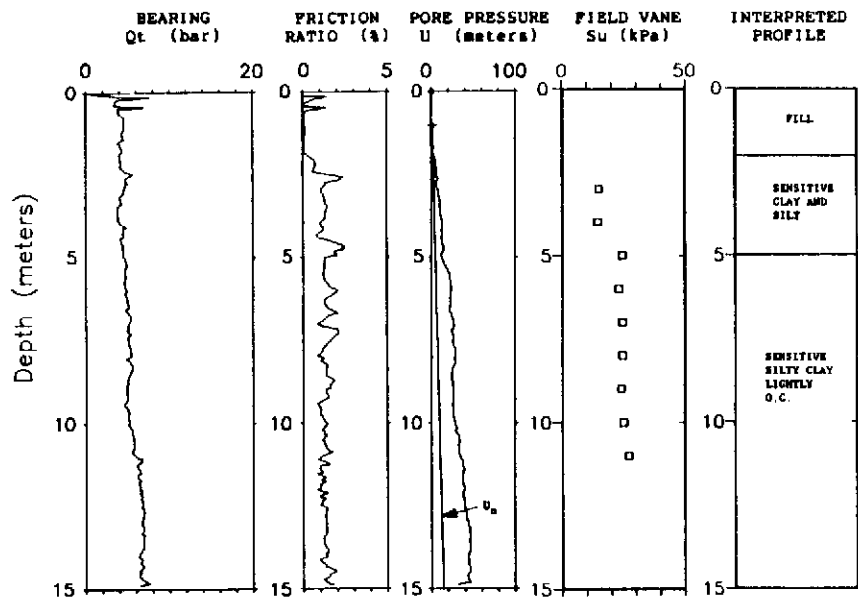


FIG. 3—Soil profile at the Cloverdale site.

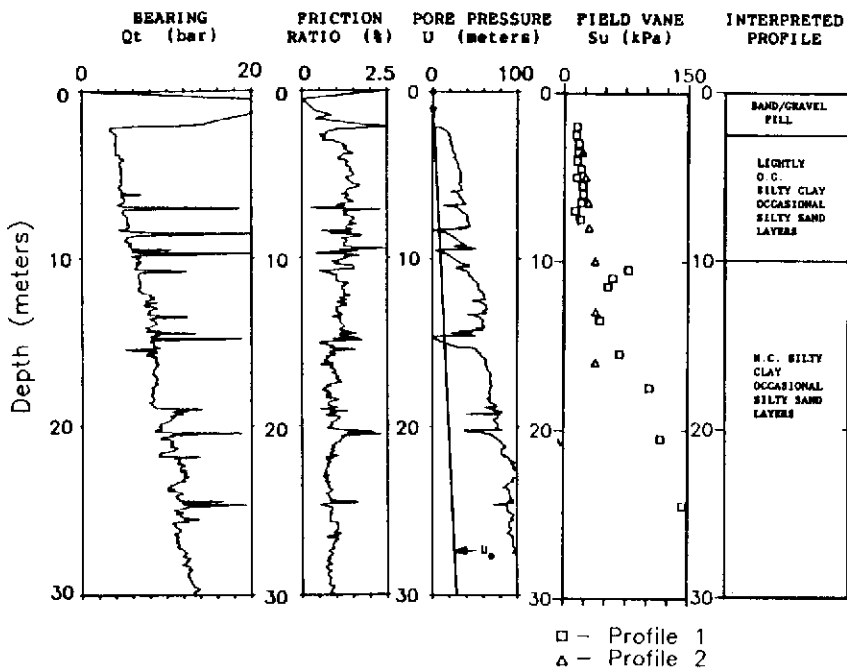


FIG. 4—Soil profile at the Langley Railway site.

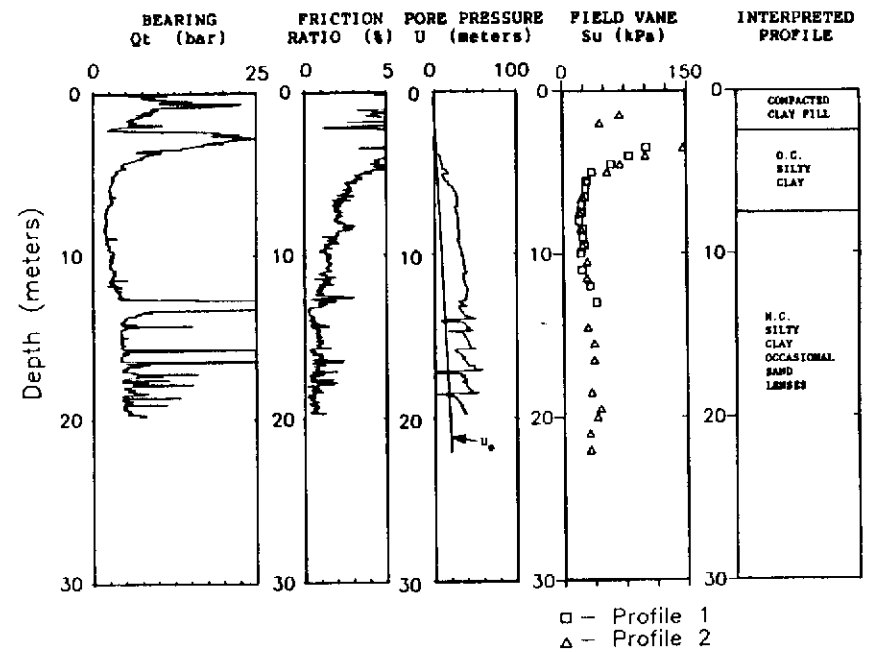


FIG. 5—Soil profile at the Upper 232nd St. site.

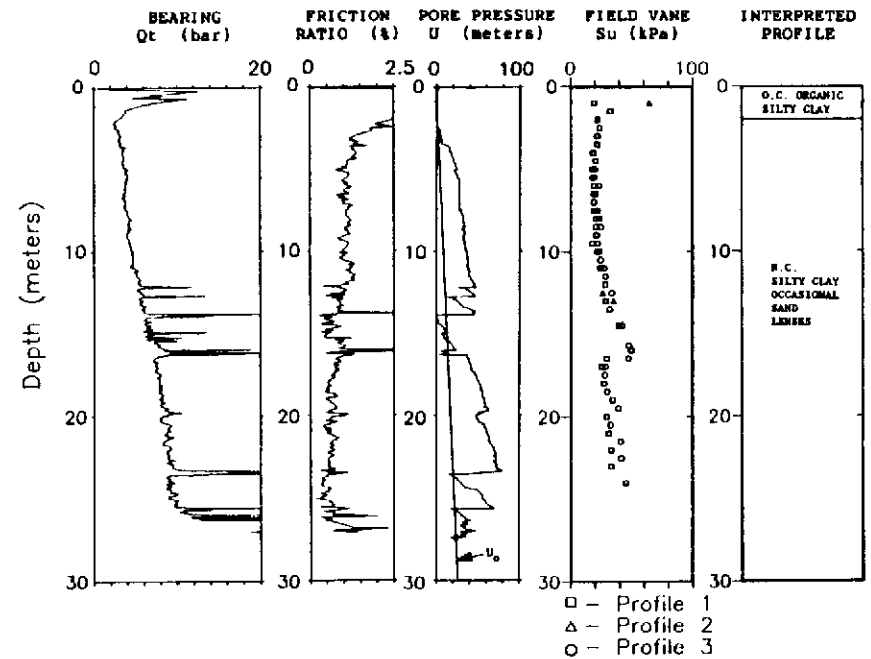


FIG. 6—Soil profile at the Lower 232nd St. site.

Test Equipment

The following is a list of the equipment (and their abbreviations) used through the course of this study:

1. Geonor and Nilcon Field Vane (FVST) [2,6].
2. Standard Marchetti Flat Plate Dilatometer (DMT) [7,8].
3. Double Helix Screw Plate (SPLT) [9,10].
4. Hughes Self Boring Pressuremeter (SBPM) [11].
5. Hughes Full Displacement Pressuremeter (FDPM) [12].
6. Roctest Pencil Probe (FDPM) [12].
7. UBC Piezocone (CPTU) [6,13].

Full details regarding the test equipment can be found in the references cited. A summary of the field tests conducted at each site is given in Table 3.

Analysis of Test Results

The following is a brief description of the methods used to analyze the data. A summary of the methods used is presented in Table 4.

Field Vane Shear Test (FVST)

All field vane undrained strengths were calculated using the standard expression (ASTM Method for Field Vane Shear Test in Cohesive Soil [D 2573]) for vanes with a length to diameter ratio of two

$$S_u = \frac{6T}{7\pi D^3}$$

where

- S_u = undrained shear strength,
- T = applied torque, and
- D = diameter of the vane.

TABLE 3—Summary of field tests conducted at the UBC research sites.

Tests	Sites				
	McDonald Farm	Cloverdale	Langley Railway	Upper 232nd	Lower 232nd
Geonor field vane (FVST)	x	...	...	...	...
Nilcon field vane (FVST)	...	x	x	x	x
UBC Piezocone (CPTU)	x	x	x	x	x
Dilatometer (DMT)	x	x	x	x	x
Screw plate (SPLT)	x	x	x	...	x
Self-boring pressuremeter (SBPM)					
Hughes	x	...	...	...	...
Full displacement pressuremeter (FDPM)					
Hughes	...	...	x	x	...
Roctest pencil probe	...	...	...	x	...

NOTE: x indicates that the test was performed at the site.

TABLE 4—Summary of the interpretation methods used.

Method	S_u
Field vane shear test (FVST)	$S_u = \frac{6T}{7\pi D^3}$ for $\frac{L}{D} = 2$
Dilatometer (DMT)	S_u from program DILLY4 (empirical)
Screw plate (SPLT)	$S_u = \frac{P_{ult}}{9.0}$
Pressuremeter (SBPM and FDPM)	$S_u = \frac{(P_1 - P_0)}{1 + \ln(G/S_u)}$
Cone penetrometer (CPTU)	$S_u = \frac{Q_t - \sigma_{vo}}{N_{kt}}$ (for bearing)
	$S_u = \frac{U - U_0}{N_{\Delta u}}$ (for pore pressure behind the tip)

There has been much discussion [1,2,6] as to the correct interpretation of the vane test; however, most engineers appear to use the above expression. No correction factors (for example Bjerrum's [14] or Aas et al. [15]) were applied to the vane data.

Flat Plate Dilatometer Test (DMT)

The DMT data were analyzed using the standard dilatometer reduction routines, DILLY and DILLY4, supplied by GPE Inc. of Gainesville, FL. These reduction routines calculate S_u using an empirical correlation proposed by Marchetti [7].

Screw Plate Test (SPLT)

The screw plate data were analyzed using the method suggested by Selvadurai et al. [10]

$$S_u = \frac{P_{ult}}{9.0}$$

where P_{ult} = ultimate failure stress to cause plunging of the screw plate.

Pressuremeter Tests (SBPM and FDPM)

All of the pressuremeter test results were analyzed using the method developed by Gibson and Anderson [16]

$$S_u = \frac{(P_1 - P_0)}{1 + \ln(G/S_u)}$$

where

- P_0 = lift off pressure,
- P_1 = limit pressure,
- G = shear modulus,
- S_u = undrained shear strength, and
- G/S_u = rigidity index.

In this study estimates of the rigidity index were made using the curves presented by Ladd et al. [17] and a knowledge of plasticity index (PI).

Cone Penetration Test (CPTU)

The cone bearing Q_t and excess pore-pressure measurements ΔU were used to estimate S_u from CPTU data. All cone bearing data were corrected for temperature and pore-pressure effects [3,6]. Estimates of S_u from the cone bearing were made using the cone factor N_{kt} [18] where

$$S_u = \frac{Q_t - \sigma_{vo}}{N_{kt}}$$

where

- Q_t = cone bearing corrected for pore-pressure and temperature effects,
- σ_{vo} = total vertical stress, and
- N_{kt} = empirical cone factor.

Estimates of S_u from penetration pore pressures measured behind the tip were made using the pore-pressure factor [18,19] $N_{\Delta U}$

$$S_u = \frac{\Delta U}{N_{\Delta U}}$$

where

- $\Delta U = U - U_0$,
- U = penetration pore pressure,
- U_0 = equilibrium pore pressure, and
- $N_{\Delta U}$ = empirical pore-pressure factor.

Several other methods of estimating S_u from CPT and CPTU (piezocone) have been suggested [6,18,19,20]; however, only the two methods described above were used in this study.

Discussion of Results

The test results for each site are presented in Figs. 7 through 11. The following is a brief discussion of the results from each research site.

McDonald Farm

The two field vane profiles (Fig. 2) are reasonably consistent with both indicating that S_u increases linearly with depth. The FVST profiles indicate a soft layer at about 20 m; however, no evidence of this could be seen in the CPTU profile. Although the shape and the trend of the DMT profile (Fig. 7) are very similar to those of the FVST, the results are consistently 20 to 30% lower. The results from the two SPLT profiles exhibit considerable scatter. However, below 18 m there appears to be a trend that is consistent with the field vane although 40 to 50% higher. The SBPM results are consistent with those from the field vane, although some low values from the SBPM were recorded between 21 and 24 m. Very

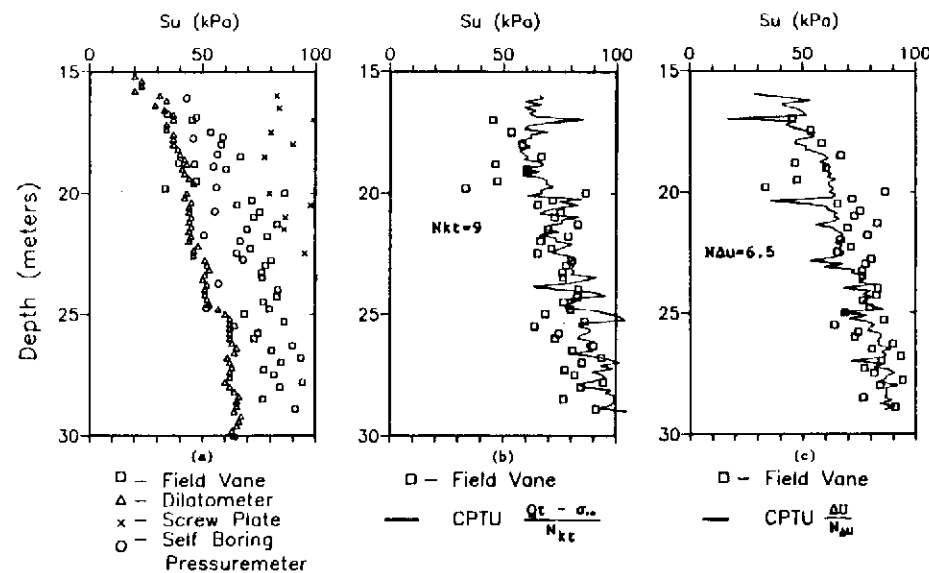


FIG. 7—Field test results at the McDonald Farm site: (a) various in-situ tests, (b) S_u estimated from CPTU bearing Q_t , and (c) S_u estimated from CPTU pore pressures.

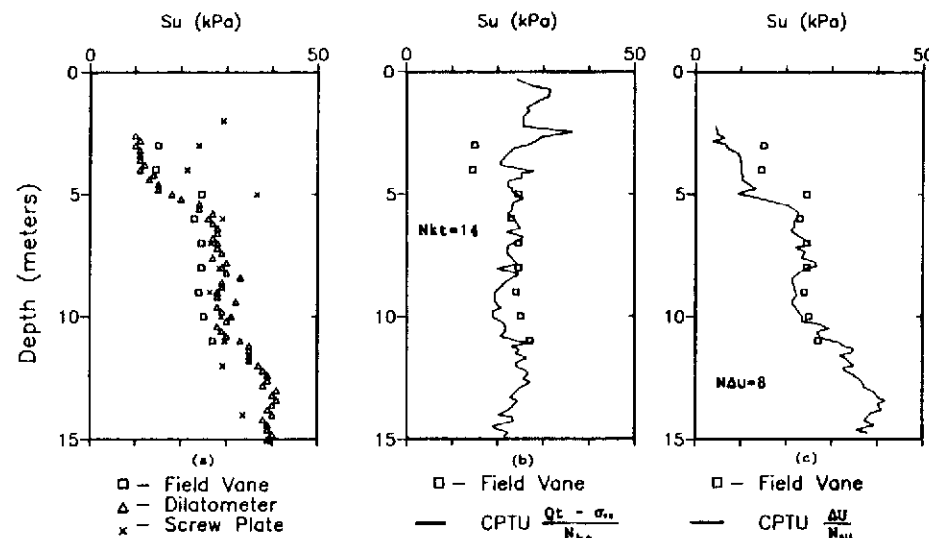


FIG. 8—Field test results at the Cloverdale site: (a) various in-situ tests, (b) S_u estimated from CPTU bearing Q_t , and (c) S_u estimated from CPTU pore pressures.

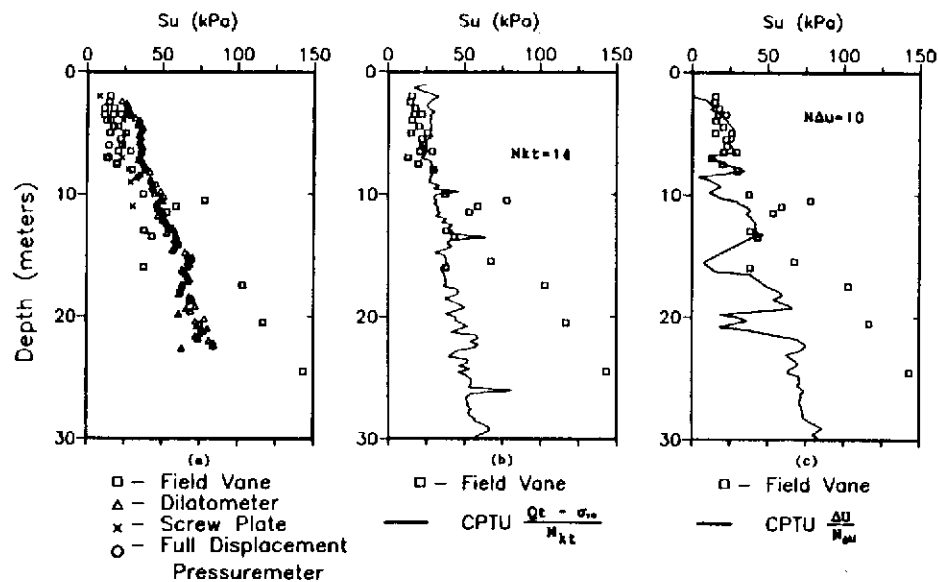


FIG. 9—Field test results at the Langley Railway site: (a) various in-situ tests, (b) S_u estimated from CPTU bearing Q_t , and (c) S_u estimated from CPTU pore pressures.

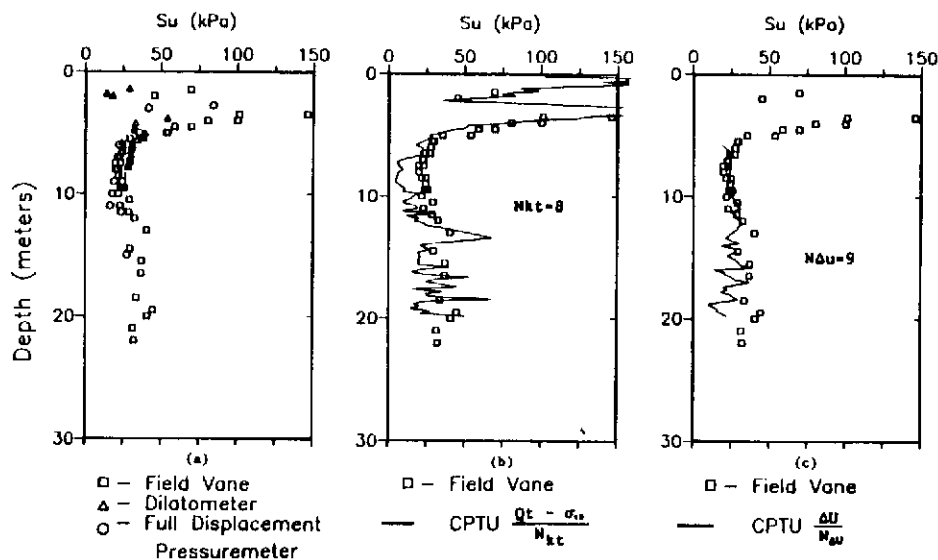


FIG. 10—Field test results at the Upper 232nd St. site: (a) various in-situ tests, (b) S_u estimated from CPTU bearing Q_t , and (c) S_u estimated from CPTU pore pressures.

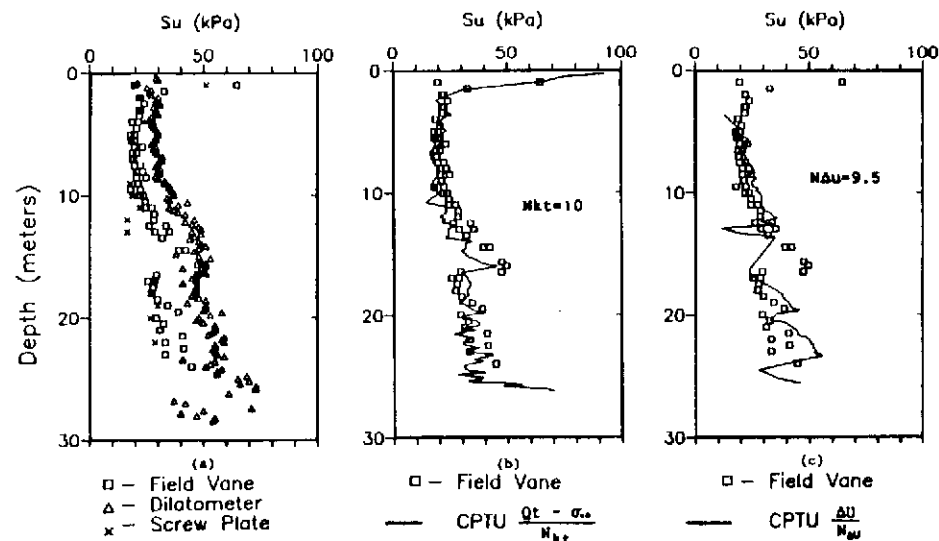


FIG. 11—Field test results at the Lower 232nd St. site: (a) various in-situ tests, (b) S_u estimated from CPTU bearing Q_t , and (c) S_u estimated from CPTU pore pressures.

good agreement between estimates of S_u from Q_t and FVST were obtained using a cone factor $N_{kt} = 9$. Some local high values in the CPTU bearing data are due to the influence of thin sand lenses.

Using $N_{\Delta u} = 6.5$, very good agreement is observed between estimates of S_u from CPTU pore-pressure data and FVST results. Some low values are again due to the influence of thin sand lenses.

Cloverdale Site

The FVST profile (Fig. 3) indicates a slightly softer material above 5 m and a uniform deposit below 5 m that exhibits only a slight increase in S_u with depth. Both the CPTU and DMT data indicate a light overconsolidation above 10 m. The DMT S_u results (Fig. 8) follow the field vane trend very well being only slightly low above 5 m and slightly high below 5 m. The SPLT results compare well to the field vane below 5 m but are high and scattered above 5 m. Estimates of S_u from CPTU data agree well using a cone factor $N_{kt} = 14$ and a pore-pressure factor $N_{\Delta u} = 8$. It is of interest to note that the shape of the DMT profile is almost identical to that from the $\Delta U/N_{\Delta u}$ profile, suggesting that the DMT predominantly measures pore pressures in soft clay [20].

Langley Railway Site

The two-field vane profiles shown in Fig. 4 differ considerably below a depth of 7 m. Four field vane values of S_u are significantly larger than the remaining FVST values. These high values of S_u appear to have been caused by thin sand lenses that are clearly visible from the CPTU profile in Fig. 4. A continuous borehole sample obtained at the site [6] confirmed the existence of frequent fine sand lenses throughout the profile. The CPTU

sampling rate (25 mm) is significantly higher than the typical 1-m interval for the FVST. The results in Fig. 9 demonstrate that the relatively wide sampling intervals used in the FVST can lead to erroneous results and false conclusions if the clay layer is not homogeneous. The DMT results again reflect the general trend of the field vane but are consistently higher by approximately 30%. Very good agreement is observed with the SPLT and FDPM results. The CPTU results compare well above 16 m using $N_{kt} = 14$ and $N_{\Delta U} = 10$. It is difficult to assess how well the estimates of S_u from CPTU compare below 16 m because of the lack of good FVST results.

Upper 232nd St. Site

The two FVST profiles (Fig. 5) are consistent and clearly indicate the overconsolidation above 7 m. The field vane profiles do not appear to have been influenced by sand lenses, although significant sand lenses are apparent from the CPT profile (Fig. 5). The S_u values determined from the DMT (Fig. 10) were considerably less than those from the FVST in the overconsolidated material above 5 m. Below 5 m the DMT values were on average 40 to 50 percent greater than the FVST values, however, the two profiles displayed similar trends. Results from the FDPM tests compare well with the FVST except for the slightly low values between 9 m and 11 m and where the OCR is high. The poor agreement where the OCR is high may be a result of the pressuremeter tests not reaching a true limit pressure. S_u values from the CPTU data using $N_{kt} = 8$ compare favorably with FVST values except between 7 and 9.5 m where the CPTU values are low. Agreement is very good where OCR is high. S_u values from ΔU show good agreement in the uniform material between 6 and 12.5 m using $N_{\Delta U} = 9$. Below 12.5 m, there is a strong influence of sand lenses. Estimates of S_u in heavily overconsolidated materials can not be made from ΔU when the pore pressures have been measured behind the tip [19].

Lower 232nd St. Site

The three field vane profiles (Fig. 6) are very consistent showing a trend of S_u linearly increasing with depth except between 14 and 17 m where there appears to be a substantial increase in S_u . This change in the profile is coincidental with the sand lenses detected by the CPTU. The CPTU and FVST profiles are similar in shape. The CPTU pore-pressure profile was significantly influenced by the sand layers (Fig. 6). The DMT results (Fig. 11) are consistently higher by about 50%; however, the trend of the field vane was followed very well. Estimates of S_u from the screw plate test show very good agreement except for the low values between 12 and 13 m. S_u values obtained from CPTU results compare well in both the normally and overconsolidated regions using $N_{kt} = 10$. Estimates of S_u from CPTU excess pore-pressure measurements compare favorably using $N_{\Delta U} = 9.5$.

Summary and Conclusions

This paper has presented a comparison of undrained shear strength results from the field vane shear test with those obtained by the flat plate dilatometer, screw plate, pressuremeter, and piezocone tests at five sites in the lower mainland near Vancouver, British Columbia, Canada. A summary of the results is shown in Table 5. The results clearly show that for each type of test there is no unique factor that can be used to estimate equivalent FVST S_u values for all types of clay. This is because S_u itself is not a unique parameter but depends on the type of test, the rate of strain, and the orientation of failure planes. Each of the in-situ tests used in this study shears the soil in a different manner and at a different strain rate, and can therefore be expected to produce different results.

TABLE 5—Summary of in-situ measurements of undrained shear strength compared to the field vane shear test.

Site	S_u^a	OCR	DMT	SPLT	PM	In-Situ Test Method	
						Bearing Q_t	Pore Pressure Δu^b
McDonald Farm	2 to 7	NC	20–30% lower but similar trend	40 to 50% higher	self boring; consistent	$N_{kt} = 9$ consistent	$N_{\Delta u} = 6.5$ consistent
Cloverdale <5 m	10 to 27	2 to 5+	slightly lower	high and scattered	...	$N_{kt} = 14$ 50% higher	$N_{\Delta u} = 8$ 30% lower
>5 m	8 to 29	1 to 2	consistent	consistent	full displacement	$N_{kt} = 14$ consistent	consistent
Langley Railway <7 m	4 to 10	1 to 3	30% higher but similar trend	consistent	consistent	slightly higher	consistent
>7 m	7 to 11	NC	30% higher but similar trend	consistent	consistent	consistent	consistent where not influenced by sand layers
Upper 232nd St. <7 m	2 to 7	1 to 10+	lower in fill at shallow depth (<3 m) then 40% higher 50% higher (similar trends)	...	lower in fill at shallow depth (<3 m) then consistent	$N_{kt} = 8$	$N_{\Delta u} = 9$
>7 m	7 to 19	NC	50% higher but similar trend	consistent	consistent	slightly lower	consistent except where sand had strong influence
Lower 232nd St. <5 m	7 to 10	1 to 7+	50% higher but similar trend	consistent	...	$N_{kt} = 10$	$N_{\Delta u} = 9.5$
>5 m	10 to 19	NC	50% higher but similar trend	10 to 20% lower	...	very consistent	can not use where clay is heavily O.C. or unsaturated
						consistent	consistent where not influenced by sand lenses

^a Sensitivity from field vane.
^b Porous element located behind tip.

Despite their differences in failure mechanism the results obtained by the in-situ methods presented in this report tend to agree fairly well with the FVST values. However, at three of the sites the DMT results did show significant error. Encouragingly though, the overall shapes of the estimated S_u profiles from the DMT were very similar to the field vane profiles. This suggests that some flexibility with respect to the input of local correlations in the DMT reduction programs is required.

The screw plate test results were considerably higher than those from the field vane only at the McDonald Farm site again showing that local correlations are often required.

The S_u results from both the self-boring and the full displacement pressuremeters agreed well with those from the field vane. However, the results were dependent on an appropriate selection of the rigidity index G/S_u .

Very good agreement was obtained using the cone bearing and various values of the cone factor N_{kt} . It is clear, however, that there is no unique value of N_{kt} for all clays. The variation in N_{kt} is influenced by such soil properties as stress history, sensitivity, and stiffness [19]. Increases in OCR are generally reflected in increases in N_{kt} [6,18]. Data from the Langley railway site [6] also indicate that N_{kt} increases with decreasing PI. It is essential to correct CPTU bearing values for temperature and pore-pressure effects [3,6] in soft clays where bearing is low and pore pressures are high.

Good agreement was obtained using CPTU excess pore pressures measured behind the tip and various values of the pore-pressure factor $N_{\Delta u}$. No unique value of $N_{\Delta u}$ was found since the generation of pore pressures is also influenced by the soil's stress history, sensitivity, and stiffness [19]. Reasonable estimates of $N_{\Delta u}$ can be made from the rigidity index. Estimating S_u from pore-pressure measurements is highly influenced by the location of the pore-pressure element [19] and the degree of saturation in the measuring system. Estimates of S_u in heavily overconsolidated clay can not be made by this method if the porous element is located behind the tip. Estimating S_u from CPTU pore-pressure data is also significantly influenced by the occurrence of sand layers.

The existence of sand lenses can significantly influence FVST results. The relatively large depth intervals used in the FVST can lead to erroneous results and false conclusions if the clay layer is not homogeneous.

The CPTU and DMT are both logging tests that economically provide near continuous data. Results from this study show that provided the locally evaluated empirical correlation factors are applied to CPTU and DMT, data near continuous estimates of equivalent FVST S_u values can be determined.

Acknowledgments

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