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THE USE OF A FIELD VANE APPARATUS IN SENSITIVE CLAY

BY

W. J. EDEN AND J. J. HAMILTON

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THE USE OF A FIELD VANE APPARATUS IN SENSITIVE CLAY*

BY W. J. EDEN¹ AND J. J. HAMILTON¹

SYNOPSIS

The extremely sensitive deposits of post-glacial marine clay in the St. Lawrence lowlands have presented major difficulties in obtaining adequate undisturbed samples for a reliable determination of shear strength. To overcome this problem, a simple field vane apparatus was devised which was readily adaptable to existing drilling equipment. This paper describes the apparatus and outlines the method of testing that has been used in the field. Shear strength values obtained are compared with those obtained from tube samples from several test holes in Leda clay. The influence of such factors as the area ratio of the vane and rod friction are discussed along with its use as a measure of sensitivity. It is concluded that the field vane device offers a more reliable criterion for shear strength of the clay than determinations made from tube samples. Advantages and restrictions on its use are also considered.

Extensive deposits of extremely sensitive post-glacial Marine clay occur in the St. Lawrence and Ottawa Valleys. It is commonly referred to as Leda clay.

Investigations by Eden and Crawford (1)² have shown the Leda clays to have a moisture content in excess of the liquid limit and to be slightly preconsolidated. To overcome the problems of obtaining detailed information on variations in the deposit and of obtaining tube samples which would yield reliable shear strength determinations, a field vane apparatus was developed which was readily adaptable to existing test drilling equipment. This paper describes the apparatus, the procedure used for

testing, and evaluates tests using the field vane compared to results obtained from tube samples. Five sites were investigated from which tube samples were obtained and at which continuous vane tests were conducted. The tube samples were obtained using a 3-in. diameter stationary piston sampler of the following critical dimensions as defined by Hvorslev (2): 24 in. in length inside diameter 2.8 in.; Kerf ratio 17.3 per cent; and inside clearance 1.2 per cent. At each of the five sites, a comprehensive testing program was undertaken to gain a good indication of the geotechnical properties of the deposit.

DESCRIPTION OF THE APPARATUS

Two requirements in the operation of the vane equipment influenced its original design. These requirements were: (a) that the vane and torque measuring apparatus could be used in conjunction with a standard soil sampling drill rig,

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² The boldface numbers in parentheses refer to the list of references appended to this paper, see p. 53.

FIG. 1.—Field Vane.
 (a) Details of Field Vane.
 (b) Vane Apparatus Mounted on Drill Rig.
 (c) Portable Apparatus Showing Method of Measuring Torque.

to facilitate its use in boreholes, for soil sampling, and (b) that it could be used as a portable apparatus along with hand-operated augering equipment in areas where equipment access is difficult or impossible.

To comply with the first requirement, the diameter chosen for the vane was 2.80 in., since this size allows easy passage through standard NX casing. Previous investigations by Cadling and Odenstad (3) indicated that the ratio of vane length to diameter should be two, and therefore the height (or length) of vane was set at 5.60 in.

To reduce the possibility of the vane catching on the casing and to improve its driving qualities, it was provided with conical points at both ends. The vane has a standard *A* rod male coupling at the upper end of its tapered shaft. The shaft was tapered in an attempt to minimize the area ratio (defined as the ratio of the average cross-sectional area of the vane to the cross-sectional area of cylinder sheared) of the vane and yet maintain the strength necessary to develop full design strength of the vane blades (Fig. 1(a)).

Two vanes were designed, constructed, and tested. Both vanes had the same height and diameter dimensions, the principal difference being the blade thicknesses. The result of this difference in design was that the area ratio of the second vane was considerably less than that of the first. The original vane was designed to test shear strengths up to 4 tons per sq ft and had an area ratio of 25 per cent. As work in sampling of sensitive soils indicated that disturbance was related to the area ratio of the sampler, it was decided to investigate the effect of varying the area ratio on shearing strength measured with the field vane apparatus. Consequently, the second vane was designed with an area ratio

of 10.2 per cent and capable of testing shearing strengths up to 1 ton per sq ft.

The torque was applied to the drill rods through a worm gear drive mechanism which allowed close control on the rate of angular rotation of the drill rods. The worm gear drive and crank were mounted on a frame which can be bolted to the frame of a drill rig or bolted to a reaction truss which can be anchored to the ground when used as a portable apparatus (Fig. 1(b) and (c)).

Since the rotational strain in the cylinder of soil being sheared is not necessarily the same as the angular rotation of the drill rods at ground surface (at least until the applied torque equals the resisting torque due to the maximum soil shearing strength), there is in effect a controlled rate of stress application until ultimate shear occurs (which results in an approximately controlled rate of strain). When the applied torque equals the resisting torque of the soil cylinder being sheared, the rate of strain in the soil equals the applied rate of strain at ground surface and controlled rate of strain conditions exist. As shear progresses, the shearing resistance of the soil cylinder usually decreases and the rate of strain increases until the excess energy stored in the drill rod is dissipated to reestablish the applied and resisting torque equilibrium condition.

The torque drive allows controlled rate of angular rotations of 6 deg per min by turning the crank at the rate of one revolution per second. This is easily accomplished and therefore good test control is maintained.

The applied torque is determined by means of a dynamometer which measures the tangential force applied to the gear sector which turns the drill rod. The axial reaction of the worm gear shaft is transmitted to this dynamometer where deflection readings are taken. Reference

to a calibration curve gives the force applied at the known pitch radius of 13 in. By multiplying the tangential force by the pitch radius, the applied moment is determined.

The method of determining the shear formula, that is, the formula linking applied torque and the actual shearing strength measured by the vane, involved making the same assumptions as Cadling and Odenstad (3). These assumptions are:

(a) The surface of rupture is a circular cylinder surrounding the vane, with the diameter D and the height H of this cylinder equal to those of the vane, and

(b) The stress distribution at the maximum torsional moment, $M_{\max}$, is uniform across the whole surface of the cylinder, including its end surfaces.

The shear formula takes the form:

$$T = S_s K \dots \dots \dots (1)$$

where:

T = maximum applied torque,

S_s = maximum or ultimate soil shearing strength, and

K = the vane constant, depending upon the physical dimensions of the vane.

Actually,

K = cylinder area times its moment arm plus cone areas times their moment arms.

For the dimensions of the NRC vane:

$K = 85$ cu in. or 0.0492 cu ft.

Since, $T = Fd$ where:

F = force applied on gear sector measured by the dynamometer lb, and d = gear sector pitch radius, in. (13 in.)

$$\text{then, } S_s = \frac{Fd}{K}$$

and for S_s measured in lb per sq ft the equation becomes:

$$S_s = 22.08F \dots \dots \dots (2)$$

where:

F is measured in pounds.

It will be noted that no attempt has been made in this formula to correct for the effect of the resistance of "friction" that the soil offers against rotation on that portion of the vane rod below the bottom of the washed and cased hole. Since this is a variable, dependent upon the sensitivity of the soil, no simple relationship exists which would allow including a correction for this factor in this formula. The effect of "rod friction" will be further discussed later in this paper.

During the investigations, it was found that small losses in the apparatus due to friction in the bearings of the drill chuck or in the thrust bearing of the portable setup, rendered the original dynamometer calibration curve inaccurate, especially at higher shearing strengths. To eliminate this source of error, the apparatus was calibrated in simulated field test conditions throughout the desired test range. This was accomplished by a relatively simple moment arm pulley, and weight arrangement which allowed dynamic loading of the apparatus.

To evaluate the amount of torsion that occurred in the vane rod and therefore to study the actual stress-strain characteristics of the soil, it was found necessary to calibrate for the angle of twist in the rods for any moment applied. It was found that the measured and the theoretical values agreed closely and that a straight-line relationship existed, giving the equation:

$$\theta = 0.0448R \dots \dots \dots (3)$$

where:

θ = angle of twist in degrees per foot of rod, and

R = dynamometer reading times 100.

By applying this correction good

stress-strain curves were derived from the test data.

TEST PROCEDURE

Since the torque rods which turn the vane are not isolated by a casing, the test procedure must be such as to keep rod friction to a minimum. The following procedure was used in the tests reported here except for those where variations have been noted. First, a casing, large enough to pass the vane, is driven 2 ft short of the depth at which the test is to be undertaken. The casing is cleaned with a rotating washing bit. The vane is inserted into the casing and lowered to the bottom of the casing. Then, depending on the resistance of the soil, the vane is pushed into the soil until the bottom of the vane is 2 ft below the casing shoe. As the vane is advanced, care must be taken to insure that no torque is applied to the rods. In stiff soils it may be necessary to advance the vane by means of the hydraulic feed of the core drill. With the Leda class, the vane can usually be advanced by the weight of two men.

With the vane in position and the drill chuck loose, the handle of the mechanism is turned in order to obtain the inherent friction of the gear drive and the resistance of the drill rod spindle. The chuck is then tightened on the rods, and the test proceeds. The handle of the mechanism is turned at 60 turns per min, which yields an angular rotation of the vane rods of 6 deg per min. The dynamometer dial is read every 10 revolutions of the handle so that a stress-displacement diagram can be plotted if desired. After the maximum reading is obtained, the chuck is loosened, and the vane is rotated four revolutions as quickly as possible. After the fourth revolution is completed, the chuck is re-tightened, and the remolded strength determination proceeds 1 min after

completing the fourth revolution. The remolded strength is determined in the same manner as the undisturbed test.

Again the chuck is loosened and the vane is advanced 1 ft, and undisturbed and remolded strengths are determined. This process is repeated every foot until the vane tip is 11 ft below the bottom of the casing. The vane is withdrawn from the drill hole, the casing is advanced and washed a further 10-ft increment. Then vane tests are conducted for another 10 ft. In this manner both undisturbed and remolded strengths can be determined in 1-ft increments throughout the depth of the clay stratum.

The only way in which this procedure differs from vanes with a casing is that in all tests a length of drill rod varying from 1 to 10 ft is subjected to friction from the remolded clay upon the drill rod. With the extra sensitive Leda clay, the rod friction is insignificant in undisturbed tests.

Rod friction can be evaluated by inserting a drill rod fitted with a conical point into the hole and repeating the same procedure as for the remolded test. With the rod friction test, it is important to conduct the test at an interval of exactly one minute after remolding, as it has been found the Leda clays regain strength rapidly with time.

Measurements made to date indicate that rod friction varies from 0.35 lb to 2.5 lb per ft of drill rod.

RESULTS FROM FIVE LOCATIONS

Test results from five sites are presented in Figs. 2 to 6. In each case, continuous vane tests were conducted in one boring, while 3-in. diameter tube samples were obtained from another hole adjacent to the first.

Boring No. 1 (Fig. 2) was located 11 miles southeast of the center of Ottawa in an extensive level plain where the

groundwater never falls more than 4 ft below the surface.

Boring No. 2 (Fig. 3) was located in the eastern outskirts of Ottawa on a site

some Norwegian clays described by Bjerrum (4).

Boring No. 3 (Fig. 4) was located in the center of Ottawa, at the site of the

FIG. 2.—Boring No. 1, Surface Elevation 260 ft, Gloucester Township.

W_n = Natural water content, in per cent.
 L.L. = Liquid limit, in per cent.
 P.L. = Plastic limit, in per cent.
 L.I. = Liquidity Index.
 S.C. = Salt concentration, in grams per liter.
 S_r = Completely remoulded sensitivity.

featured by frequent outcrops of bedrock with intervening valleys filled with clay. Here the depth of clay was extremely variable, and the seasonal variation in groundwater is from the surface to a depth of 9 ft. The clay is fissured to a depth of 20 to 25 ft as is the case with

National Museum previously reported by Crawford (5). Here the clay also had an extensive fissured crust.

Boring No. 4 (Fig. 5) was located near the Upper Beauharnois Lock of the St. Lawrence Seaway, about 110 miles east of Ottawa. This boring is located beside

FIG. 3.—Boring No. 2, Surface Elevation 310 ft, National Research Council, Montreal Road Laboratories, Ottawa.

FIG. 4.—Boring No. 3, Surface Elevation 235 ft, National Museum, Ottawa.

FIG. 5.—Boring No. 4, Surface Elevation 146.5 ft, Beauharnois, Quebec.

FIG. 6.—Boring No. 5, Hawkesbury, Ontario.

the dike of the existing power canal. The construction of the dike in 1930 raised the level of the groundwater and changed the effective stresses on the clay stratum. This probably accounts for the preconsolidation shown in Fig. 5. Here the fissured crust extends below the depth of the original groundwater level. The field vane tests were taken at intervals of $1\frac{1}{2}$ ft in this boring.

Boring No. 5 (Fig. 6) was situated near Hawkesbury, Ontario, 60 miles east of Ottawa. This was the site of a large landslide (500,000 cu yd) which occurred in December, 1955. The clay was covered by a mantle of sand generally from 8 to 10 ft thick, although it was only 4 to 5 ft at this borehole.

From each boring, except No. 3, the following properties were determined in relation to depth: natural water content, W_n Atterberg limits, L.L. and P.L., liquidity index, L.I., which is defined as

the ratio of $\frac{W_n - P.L.}{L.L. - P.L.}$, grain size in

terms of the per cent clay sized particles (less than 0.002 mm), sensitivity, S_t as measured by the laboratory vane apparatus (expressed as the ratio of undisturbed to remolded strengths), the pore water salt concentration (S.C.) (the amount of soluble salts in the pore water of the clay expressed in grams per liter), unit weight, preconsolidation pressure, and unconfined or triaxial quick strengths. The results are plotted or tabulated in the form of average results for a 2-ft sample. The results of unconfined or triaxial quick results are plotted beside the diagram of vane strengths and are the maximum values obtained from a particular sample tube. In boring No. 3, no measures were made of sensitivity or salt concentration.

COMPARISON OF THE FIELD VANE WITH OTHER TESTS

It is apparent from an inspection of the results of the five borings that the

strengths measured by the field vane equals or exceeds the maximum values of those determined in the laboratory from tube samples. The question arises which method yields the more reliable data. It should be remembered that both field vane and laboratory tests yield data which constitute the result of a method of applying shear stresses to the clay; hence neither may represent the true shear strength under a particular set of field conditions.

The authors consider the field vane data to be more reliable than the laboratory test methods for the shear strength of Leda clay for the following reasons:

(a) Field vane tests have proven more consistent than laboratory determinations, as is evident from the logs of the five borings. The fact that wide variations occur in laboratory strength determinations within a sample tube and from one tube to another points to serious limitations in the method of sampling. The vane tests, on the other hand, are not affected to the same extent by disturbance, since the tests are conducted *in situ*. At Beauharnois, both the 25 and 10 per cent area ratio vanes gave very close comparison in the two adjacent boreholes. This would indicate that, in Leda clay, the most serious disturbance arises from the relief of stresses in the clay when the soil is removed from its natural environment.

(b) In two instances of landslides in Leda clay, the vane gave results close to those indicated by analysis of the slope failure, for example, those tabulated by Meyerhof (6). In the case of the Nicolet landslide in November, 1955, the estimated factor of safety based on field vane test results reported by Hurtubise and Rochette (7) was 1.1. At the Hawkesbury landslide, Meyerhof (6) has estimated the shear strength to be about 800 lb per sq ft for a safety factor of 1.0. It can be seen from Fig. 6 that this is close to the strength indicated by the

field vane. Although neither case has been reported to date in sufficient detail to present conclusive evidence, the field vane has in both cases proved to be fairly reliable. In the case of the Hawkes-

undisturbed strength to the remolded strength. Results presented in this paper were determined with a laboratory vane apparatus. A determination was first made on a cylinder of undisturbed clay

FIG. 7.—Relation Between Sensitivity and Liquidity Index.

bury slide, the vane strengths are definitely more reliable than those conducted on tube samples.

USE OF REMOLDED TESTS AS A MEASURE OF SENSITIVITY

The sensitivities of Leda clay are commonly 20 and sometimes exceed 100. Sensitivity is defined as the ratio of the

extracted from a sample tube. The clay was then completely remolded by a mechanical mixer, allowed to stand 1 min, then the remolded strength was determined.

Both undisturbed and remolded strengths were determined by the field vane, and hence a "field sensitivity" measure (ratio of undisturbed to re-

molded field vane strengths) was made in all five borings. It was found that determinations conducted in the laboratory on completely remolded samples were much higher than the results given by the field vane. Moreover, there was no consistent relationship between field sensitivity and the sensitivity as measured in the laboratory. A study was, therefore, made of the results of sensitivity determinations.

Bjerrum (4) has indicated a relationship between liquidity index and sensitivity. Figure 7 gives this relationship along with data presented by Bjerrum (4) and Meyerhof (6) together with results from the five borings. It can be seen that the determinations on Leda clay are in line with results from Norway and elsewhere. It was concluded, therefore, that the techniques used with the laboratory vane were comparable to those used in Norway and that the field tests were not a reliable indication of sensitivity.

The investigation was pursued further by attempting to simulate the field vane test with the laboratory vane test. First, the undisturbed strength was determined for a cylinder of soil extracted from a sample tube. The laboratory vane was then rotated quickly four revolutions. The strength of the remolded surface was then determined after 1 min rest. Finally, the sample was completely remolded with a mechanical mixer, and the completely remolded strength was determined. The results of this investigation are presented in Table I along with the corresponding field sensitivities.

From these test results it was impossible to correlate either field sensitivity with the completely remolded sensitivity or with the partially remolded sensitivity measured by rotating the laboratory vane.

Skempton (8) was successful in obtaining the same remolded strengths by field and laboratory methods. The clay

at Grangemouth as reported by Skempton and Northey (9) had an average value of sensitivity of 4.3, which is considerably less than for the Leda clays. There are two factors that have contributed to the discrepancies between the various test methods reported in Table I. First, the field vane tests a cylinder of soil approximately 8 in. high and yields

TABLE I.—COMPARISON OF THREE SENSITIVITY MEASUREMENTS.

(Samples 62-7 to 62-21 from Hawkesbury, boring No. 5 and samples 76-2 to 76-13 from Beauharnois, boring No. 4.)

Sample Number	Depth, ft	Liquidity Index	Field Sensitivity	Sensitivity by Rotating Laboratory Vane	Completely Remolded Sensitivity
62-7.....	6	1.7	4.6	4.3	12.3
62-8.....	8	1.5	5.3	5.6	12.8
62-9.....	10	1.6	7.0	4.4	9.7
62-10.....	12	1.5	4.8	4.0	10.6
62-12.....	16	1.5	3.6	10.8	26.3
62-13.....	18	1.2	2.6	6.6	12.2
62-14.....	20	1.3	2.8	3.8	30.3
62-15.....	22	1.2	2.6	10.0	23.4
62-16.....	26	1.3	2.5	3.8	9.1
62-18.....	30	1.5	11.0	4.1	49.0
62-21.....	36	1.4	4.1	8.4	33.7
76-2.....	17.5	1.5	1.2	5.8	9.4
76-4.....	21.5	1.3	4.4	7.0	12.2
76-5.....	23.5	1.6	5.1	6.4	12.6
76-6.....	25.5	1.2	2.8	4.7	22.8
76-7.....	27.5	1.7	2.1	6.2	15.4
76-8.....	29.5	1.4	2.3	4.1	7.2
76-9.....	31.5	0.8	4.7	3.9	7.4
76-10.....	33.5	1.2	2.9	7.4	10.5
76-11.....	35.5	1.2	2.2	3.7	10.8
76-12.....	39.5	0.9	2.0	4.8	9.9
76-13.....	41.5	0.9	1.9	5.6	5.3

average results for this height. The laboratory determinations were made on a cylinder of soil $3\frac{1}{2}$ in. high extracted from a tube 2 ft long. In addition, the laboratory vane is $1\frac{1}{2}$ in. high and hence it is possible that the laboratory test is conducted on a strata with significantly different properties than shown by the average values for a 2-ft tube or by the field vane test. The second factor is that

Leda clay appears to stiffen or regain some of its strength significantly with time. Studies of this feature of Leda clay are not sufficiently advanced to give any other data. It may be that hardening takes place more quickly on a remolded surface than in a completely remolded body.

Figure 7 shows that there is poor correlation between sensitivity and liquidity index. This would suggest that one should not attach too much significance to single values for sensitivity. It also suggests that when presenting values for measures of sensitivity it is very important to state the test method used and to note the time interval between the completion of the remolding process and the start of the strength determinations.

The authors do not wish to discredit the value of the remolded test but wish to suggest that the field sensitivity is no more than an indication of the sensitivity of the clay. Remolded field vane tests are valuable in pointing up changes in strata and are a good control on the apparatus against defective tests due to encountering a stone or poor functioning of the apparatus.

CONCLUSIONS

1. The results of the five site investigations reported indicate that the field vane apparatus provided a reasonably reliable indication of the shear strength of a sensitivity clay. For the Leda clay studied in this investigation, the authors consider the vane to give more reliable data than those obtained by conventional piston sampling and reasonably careful laboratory techniques.

2. The field vane offers considerable advantages in economy over tube sampling and laboratory testing. This is an important consideration where variations in soil properties are sought over a site

with a common geological history. The authors would not, however, recommend that the field vane be used in the absence of other data on a clay stratum. It is a tool with which variations in a stratum can be detected with little expenditure and should in all cases be supported by data on the other properties of the clay so that a comprehensive evaluation can be made of the clay deposit.

3. Based on the investigation of the five borings, the field sensitivity cannot be related to laboratory sensitivity determinations with any confidence. A better measure of sensitivity appears to be in the relation between sensitivity and the liquidity index.

4. The remolded field vane test is useful in indicating changes in strata and provides a good control on the testing technique and apparatus. It was found that the time element is important in remolded tests.

5. The apparatus reported in this paper has an element of error introduced by friction between the uncased portion of the drill rods and the remolded clay. With the highly sensitive clays reported in this paper, the rod friction is not significant. However, with similar apparatus used in less sensitive clays, evaluations should be made of rod friction to guard against any discrepancies.

6. Based on a limited investigation at boring No. 4, the difference between using field vanes with area ratios of 25 and 10 per cent is not significant.

7. The field vane described in this paper is readily adaptable to existing drilling equipment. It requires no special vane housing or casing and the rate of strain can be controlled within reasonable limits by the worm gear drive mechanism.

Acknowledgments:

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them by their colleagues of the Soil Mechanics Section, Division of Building Research of The National Research Council of Canada, in the design and use of this apparatus and in the laboratory investigations undertaken. Boring No. 4 at Beauharnois was conducted with the kind of cooperation and assistance of the

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DISCUSSION

CHAIRMAN K. B. WOODS.¹—I might mention that we used apparatus similar to the author's in an attempt to evaluate some of the banded sediments on the lower reaches of the St. Lawrence this last summer and we have been well pleased with the performance of the equipment and the data obtained.

¹ Head, School of Civil Engineering, Purdue University, Lafayette, Ind.

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