Type of Problem	Type of Clay	
	Normally Consolidated	Overconsolidated
Short-time bearing capacity (No drainage)	Correct	Correct
Long-time bearing capacity	Conservative	Unsafe?
Slopes of temporary cuts (No drainage)	Correct	Correct
Slopes of long time cuts	Unsafe (Swelling)	Unsafe
Natural slopes	Conservative to correct	Unsafe

may be explained. The tests in the Gulf of Mexico reported by W. Fenske show the consolidated undrained shear strength values to be smaller than the field vane test values. A reverse relation seems to be valid in our clays (*1*). The clay tested in the Gulf of Mexico is overconsolidated while the clay referred to in Sweden is normally consolidated. Considering the different recompression characteristics of an overconsolidated and a normally consolidated clay when the calculated overburden pressure is applied to the sample the different relations obtained seem to be explained.

REFERENCES

(1) L. Cadling and S. Odenstad, "The Vane Borer," *Proceedings, No. 2,* Royal Swedish Geotechnical Inst., Stockholm (1950).

(2) Various papers and discussions in *Proceedings*, European Conference on Stability of Earth Slopes, Vol. 1–3, Stockholm (1954 and 1955). (Note specially Opening Address and Discussion by A. W. Skempton in Vol. 3.)

(3) Lecture by L. Bjerrum, "Stability of Natural Slopes," held at a meeting at the Swedish Geotechnical Society in Stockholm on Dec. 15, 1955. (Unpublished.)

(4) L. Bjerrum, "Theoretical and Experimental Investigations on the Shear Strength of Soils," Norway Geotechnical Inst., *Publication No. 5,* Oslo (1954).

GENERAL DISCUSSION

MR. WILLIAM S. HOUSEL.[11]—One question I would like to raise has to do with the rate of loading, both in the laboratory and in the field. Mr. Gibbs mentioned in his paper that there was a variation in shearing resistance due to the rate of loading, the rate at which the vane was rotated. In comparison, however, with the laboratory tests, it was not stated what rate of loading was used in the triaxial compression tests or the unconfined compression tests, and what basis there was for comparing them with the rate of loading in the field.

Those who are familiar with the static shearing resistance or yield value test, which is used in the University of Michigan laboratory, know that the observations are extrapolated to a zero rate of deformation. There is a four-to-one ratio between the results from that test and the results from the unconfined compression test which is run in a 5-min loading period.

In other words, from the 5-min or rapid unconfined compression test, the shearing resistance value is four times the value which we obtain from the ring shear test in which the rates of deformation are extrapolated to zero rate of deformation.

These observations show that there is a wide variation in shearing resistance due to rate of loading that must be accounted for in some way. That four-to-one ratio as shown in the data which

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were presented in my paper[12] has been confirmed consistently on thousands of tests in which the ring shear test and the unconfined compression test have been run in parallel since 1939, on all investigations. Since that ratio has been thoroughly demonstrated, the question then comes up in connection with the vane shear test with a rate of loading such as is used in the field, which it is recognized must be controlled, what is the comparison between that shear value and what might be called a true or static yield value. In other words, how do the shear values in field and laboratory compare with the data which we have been presenting which show the relation between the rapid shear test and the static yield value. The question may also be put as follows: how is the rate of loading controlled, particularly in correlating the vane shear tests in the field with unconfined compression tests in the laboratory?

It seems to me that it is not enough to compare directly a rate of rotation in the vane shear test with a rate of loading in the unconfined compression test. It would appear that by definition the rates of shearing displacement on the shearing planes or surfaces would have to be the same for direct comparison, or some basis of correlation would have to be established. In other words, the peripheral speed of the vane would have to be the same as the rate of shearing displacement in the unconfined compression test. It does not appear that either of these rates has been definitely established in the tests in which they are involved. The only other valid basis on which a comparison could be made would be by extrapolating rates of shearing displacement and shearing stress to a zero rate of deformation. Such extrapolation is in strict accordance with the accepted definition of yield value and is the procedure used in the ring shear test referred to in the preceding discussion.

I would like to comment on the remolded shear strength. In my paper referred to previously[10] the results of pile loading tests in soft plastic clay throw some light on the conditions under which cohesive soils suffer a loss in shearing strength. In loading tests on a steel cylindrical pile, the pile was carried through repetitive loading cycles in which the pile in each successive cycle was loaded well into the stage of rapid progressive settlement. It was found that such shearing displacement under static load did not impair the original shearing resistance at all. On the other hand, it was found that a very large part of the side shear on such piles could be destroyed by driving the pile. Whether this loss of strength under dynamic impact represents remolding may be a matter of definition.

I have always felt that this phenomenon was closely associated with molecular orientation of the adsorbed moisture and was not necessarily the same as disturbance due to remolding. I note that there is considerable difference of opinion as to what constitutes remolding in the vane shear test. I would question whether this can be controlled by reversing the rotation of the vane, the number of turns of the vane, the speed of rotation, or any such simple procedure. The phenomenon is a complex one, and until much more is known about it and the vane shear test, there will be many questions unanswered.

I want to bring up again the rate of loading, which still seems much too indefinite. Until it is more accurately controlled it seems futile to discuss and compare various shear values. Consequently, the vane shear test can scarcely be considered a completely reliable tool

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[12] W. S. Housel, "Field and Laboratory Correlation of the Bearing Capacity of Hard Pan for Design of Deep Foundations," *Proceedings*, Am. Soc. Testing Mats., Vol. 56, p. 1320 (1956).

until the rate of loading is properly controlled.

These comments can be illustrated by one direct experience which I have had with the vane shear test. A little more than a year ago, the Detroit Edison Co. conducted an electro-osmosis experiment in which the University of Michigan Soil Mechanics Laboratory collaborated. Leo Casagrande was retained as a consultant and the actual work was performed by the American Dewatering Corp. The soil was a very soft plastic clay, typical of the Detroit, Mich., area. Periodic samples were taken and both field and laboratory shear tests were conducted. The American Dewatering Corp. elected to use the vane shear test, and samples were also obtained for ring shear tests and unconfined compression tests in the laboratory.

While it was known that there were changes in moisture content after certain periods of treatment, the vane shear tests did not reveal any significant changes in shearing resistance and were abandoned before completion of the experiment. On the other hand, the laboratory shear tests on the core samples $1\frac{3}{8}$ in. in diameter did show a consistent correlation with changing moisture contents as the experiment proceeded. This was true of the unconfined compression tests, but the results of the ring shear test were even more significant. Being a sedimentary deposit, the lacustrine clay was a stratified deposit. The effect of the electro-osmosis varied with the texture and permeability of the soil layers. Correspondingly the changes in shearing resistance varied, a fact which was revealed most clearly by transverse shear in the ring shear test which acts on planes parallel to the bedding planes in the clay.

The data presented from the vane shear tests in this symposium seem to indicate a need for more study of the effect of the rates of loading before the test can be used with confidence. On the electro-osmosis experiment, the precise control of the time factor in the ring shear test paid dividends and the results demonstrated the reliability of the static yield value as a measure of soil shearing resistance.

One observation that I would like to make in connection with Mr. Fenske's paper is in reference to Fig. 7 (see p. 21). In leveling data, particularly with respect to the minimum shearing resistance, it may be noted that from a depth of approximately 50 to 150 ft, the actual in-place shearing resistance may be more closely approximated not by a straight line that varies with the depth but by a straight line in which the shearing resistance is constant with respect to the depth.

It is true that in a variable deposit the shearing resistance may vary with the depth, and that is the sort of thing that we have found in many of our tests. However, in plastic saturated clays, we have generally found that shearing resistance is independent of the depth and the varying normal pressures that are acting. While there was some stratification shown in this boring, it is indicated that for a considerable part of the depth to which I refer there was a highly plastic, saturated clay. In this case, I would certainly raise the question as to whether in leveling the data you should not follow the actual results much more closely than you do when you level it on the basis of a straight line varying with the depth.

MR. D. M. BURMISTER.[13]—The fundamental mechanics of in-place shear testing by the vane method has puzzled me for some time. At first thought, it would seem that this method by careful tech-

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niques should yield shearing strengths of clay soils, which most nearly approach the true undisturbed in-place values. But on the contrary, the values obtained are only of the same order, as those obtained by unconfined compression tests on good undisturbed samples. In the vane test the natural state of stress existing in the ground probably remains substantially unaltered, especially the important lateral confining stress, and the disturbance effects can be kept small.

In the unconfined compression test, however, the natural unequal vertical and horizontal state of stress in the soil structure and the important natural restraint conditions are removed by taking a sample from the ground, and are partially replaced by a uniform state of stress of lower but indeterminate magnitude. The new and changed stress conditions are due to capillary forces, which have been brought into action by some slight expansion of the clay soil accompanying relief of stress. In addition there are indeterminate sampling and preparation effects, which always tend to decrease the shearing strength. As a consequence, it would be expected that the unconfined compression test would yield shearing strength values somewhat smaller than in-place values. Triaxial compression tests, in which the natural stress conditions have been restored on the specimen by consolidation, indicate that about one-half to three-quarters of the maximum shearing strength is obtained by the unconfined compression test.

The unconfined compression test is at best an imperfect basis for comparison and is therefore not realistic and suitable as a true measure. Unfortunately there are and can be no real standards of reference for comparison of the strength values and properties of soils, such as exist for the common structural materials. This is due to the very nature of soils and to their marked susceptibility to the influences of varying environmental conditions and of changed imposed conditions. All that can be done is to approach the true shearing strengths of soils by improved and refined methods and techniques, which reduce disturbance effects and which test clay soils under representative and essentially identical stress and restraint conditions, as may exist in the natural state in-place. This gives point to the fact that, if the vane test strength is of the same order as that of the unconfined compression test, there must be some basic reasons inherent in the vane test method itself for this imperfection, but quite different from the imperfections inherent in the unconfined compression test.

The imperfections in the vane test are probably of the same nature as those inherent in the direct shear test, where: (1) the plane or surface of shearing failure is forced to follow a prescribed path, (2) shearing stresses are mobilized first and concentrated at the rigid metal cutting edges, and (3) the thickness of the shearing zone is forced to be unnaturally thin. Photoelastic studies of stresses in gear teeth, punching dies, etc. have clearly revealed the existence of extremely high concentrations of shearing stresses at the rigid edges of such elements and the accompanying characteristic pattern of shearing stresses.

Furthermore, the stress-strain relations of clay soils exhibit certain characteristic and inherent features, which govern the responses and performances of clay soils under stress. These characteristic features range between rather wide limits, as indicated in the following figure for controlled strain-rate testing. In a homogeneous clay soil, which has been consolidated only under light overburden, soils are under a light state of pre-stress and possess relatively low natural shearing strengths. They exhibit stress-strain curves having the characteristic form of curve (*a*) in Fig. 8. Typically a large amount of strain is required to bring such soils to their maximum shearing strength, usually exceeding 10 to 20 per cent strain. The shearing strength remains constant at its maximum value with little or no stress - drop-off effects. In such types of clay soils it would be expected that the vane shear begins to exhibit the characteristic form of curve (*b*) in Fig. 8. The stress-strain curve now exhibits a pronounced and characteristic peak of shearing strength, which is always followed by a rapid and marked stress - drop-off effect after reaching the peak of strength. These clay soils also require smaller strains, as the shearing strength increases with the state of pre-stress, to bring them to the

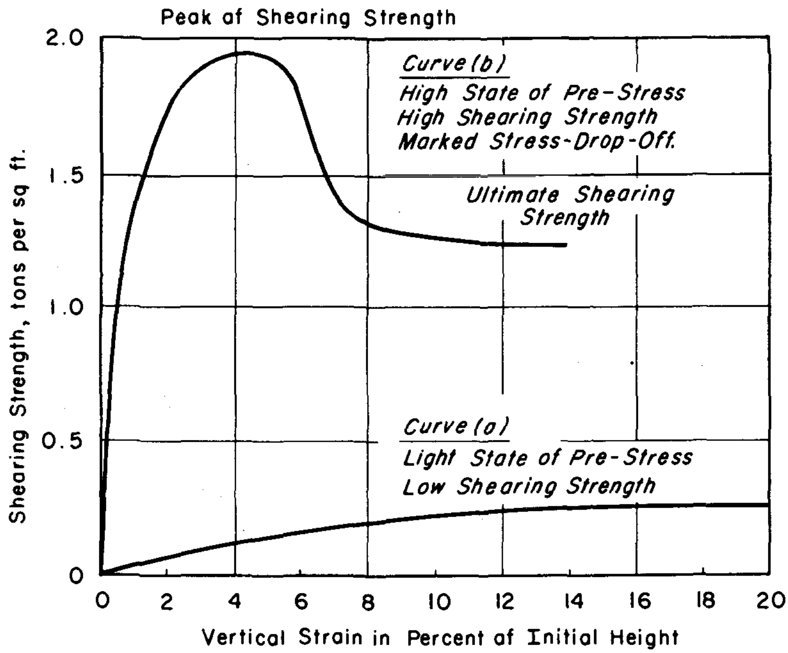

FIG. 8.—Stress-Strain Curves for Extreme Cases of Homogeneous Clay Soils.

test would yield approximately the true maximum shearing strength, because with large strains required to reach the maximum shearing strength, the stress concentration effects at the cutting edges remain small. Hence it is probable that the full maximum shearing strength can be mobilized finally along the entire length of the shearing surface.

But conditions become quite different for homogeneous clay soils, where the natural state of pre-stress exceeds some value, such that the stress-strain curve peak of shearing strength, as low as 2 to 5 per cent strain. For all such clay soils, the concentration of shearing stresses at the rigid cutting edges of the vanes becomes a pronounced and controlling part of the testing phenomena. This is entirely an artificial condition created by the test apparatus, and is not representative of any natural shearing phenomena. As a result at the cutting edge the clay soil at small strains is carried over the peak of shearing strength into the stress region of lower mobilizable shearing strength beyond by straining. Successively at increasing distances from the immediate cutting edges, but probably with decreasing effects, the clay soil by straining is also carried over the peak of shearing strength. As a consequence, in such a type of test on highly prestressed clay soils, the full maximum shearing strength can never be mobilized simultaneously along the entire length of the shearing surfaces between vanes. The stress - drop-off may be as low as 60 to 80 per cent of the peak shearing strength. The test shearing strength therefore lies somewhere between the peak of strength and the ultimate shearing strength, as noted in Fig. 8. Hence for such clay soils the vane test shearing strengths accordingly represent only some indeterminate percentage of the peak maximum shearing strength in-place, which can not be evaluated. The final goal of shearing strength testing of clay soils is not just to be conservative, but to determine the real maximum shearing strength by suitable soil testing, and then to apply a realistic margin of safety to the test values in making practical applications.

In clay soils, which are non-homogeneous in some respect, the results of unconfined compression and direct shear tests are completely dominated by the details of their non-homogeneous structure, such as: (1) the fissured and fragmentary structure of clay soils taken from the desiccated zone of weathering, (2) alternating weaker and stronger layers in thin layered or varved silts and clays, and (3) the presence of small imperfections in a sample, such as, concretions, small stones, shells, cracks, etc. These details control in a small specimen, but may have little influence in the responses of the soils under stress in large masses. In the author's experience all such soils exhibit surprisingly low shearing strengths by unconfined compression and direct shear tests, which are at marked variance with the natural consistency of these soils, as indicated by simple "feel" of the soils. The writer has come to the conclusion that the true natural in-place shearing strength of clay soils can be approached and thus approximately evaluated only by representative triaxial compression tests. As a basic test condition, the natural state of stress, which is representative of that existing in-place, and other significant controlling conditions, both as to character and magnitude, must be approximately restored on a test specimen by consolidation, followed by triaxial shearing under conditions representative of the natural situation, such as, "open or closed system" drainage, rate of shearing, etc. The basic shearing test problem is, first, to learn what being representative really means in each situation, and second, to learn how it can be attained practically and consistently in shear testing.

CHAIRMAN, J. O. OSTERBERG.[14]—The comments of Professors Housel and Burmister raise several questions concerning the validity of the vane test and the relation between it and various laboratory strength tests. Three principal questions raised concern: 1) the rate of loading, 2) the effect of remolding and 3) the actual stress conditions on the failure plane.

In answer to Housel's question and comments concerning the rate of loading, the writer knows of only two studies made concerning the effect of rate of loading on strength with the vane test. In the work of L. Cadling and S. Odenstad (Reference (1)), tests were made at various rates of rotation at various depths from the ground surface. It was found that as the rate of rotation decreased, the strength decreased, and

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that if the strength *versus* angular velocity curve is extrapolated to zero, the strength indicated for zero rate of angular velocity is within a few per cent of that indicated at 0.1 deg per sec. Also, tests at smaller rates of angular velocity seem to indicate higher strengths. Since this rate of angular rotation gives the minimum strength and since it takes from 2 to about 15 min to make a test at this rate, which is about the same time as is ordinarily taken for an unconfined test, this rate was chosen as a standard.

Tests by A. W. Skempton (Reference (2)), simply compared the results of vane tests made at various speeds of rotation with the ordinary unconfined compression test taking from 3 to about 10 min. He concluded that strengths obtained from the vane test which takes about the same time as the laboratory unconfined test to perform, gave the same results.

The writer cannot agree with Housel that there is considerable difference as to what constitutes remolding in the vane shear test. The vane must simply be rotated a sufficient number of times so that complete remolding occurs. Data in this symposium and elsewhere in the literature show excellent agreement between remolded tests in the field with the vane and unconfined or cone penetration tests in the laboratory.

W. S. Housel's comment that shearing strength for saturated plastic clays is constant with depth simply does not agree with the large amount of data published in *Geotechnique*, in the publications of the Norwegian Geotechnical Institute, and the proceedings of the Stockholm European Conference on Stability of Earth Slopes. In normally consolidated clays, the constant increase in strength with depth is so consistent, that the constant c/p ratio, or shear strength over overburden pressure, is increasingly being quoted with other clay properties. For over-consolidated clays, glacial clays, and many river deposited clays highly stratified with sand and silt seams, shear strengths do not increase with depth and may very well be constant with depth in some instances.

Concerning D. M. Burmister's remarks about the stress conditions along the failure surface in a vane test, it certainly is true that the actual stress conditions are unknown, that high stress concentrations exist on the cylindrical failure surface just in front of the vane. Progressive failure must occur along the cylindrical surface of rupture. As Burmister points out, for a brittle clay having a large dropoff in stress in an unconfined test, the vane test will give some average value rather than the peak stress. A study of the existing data comparing vane test results with unconfined tests shows that the great majority of vane tests were made on soft normally or almost normally consolidated clays which do not exhibit any marked peak and dropoff in strength as strain is increased. With brittle overconsolidated clays which show a very sharp peak and a dropoff at small strains, one should be cautious in interpreting the results of all types of tests including the triaxial. For these clays there may be a reduction of strength with time due to the gradual loss of the "prestress" and the effects of fissures and cracks may be very important.

Burmister advocates the triaxial test as the best test to duplicate conditions as they exist in place. It is true that the natural state of stress can be applied in a triaxial test and that conditions of drainage and shearing approximating field conditions can be applied. However, it is questioned whether the unconfined test should be completely abandoned and full reliance given to the triaxial test as Burmister suggests. Burmister states that disturbance due to sampling and specimen preparation always tends to decrease the shearing strength and that unconfined tests always result in strengths considerably lower than the triaxial tests. It is true that where silt seams, cracks, fissures, and organic fibers exist the lack of confining pressures to an unconfined test will result in a lower strength. However, on uniform plastic clays there are a large amount of laboratory data which show exactly the same strength for unconsolidated undrained tests as for unconfined compression tests. And these are the very types of clays in which excellent agreement is obtained with the vane test. For triaxial tests which are consolidated first, one should not attempt to compare them with unconfined tests. If the clay being tested is disturbed, as all laboratory specimens are to some degree, then if it is reconsolidated to a stress less than the preconsolidation stress, the effect of disturbance is to decrease the strength over the true undisturbed strength. But if the clay is reconsolidated to a stress larger than the preconsolidation stress, the effect of disturbance is to cause a larger strength than the true undisturbed strength. This is due to the fact that when partially disturbed, a clay will consolidate to a smaller void ratio when consolidated to a stress higher than the preconsolidation stress than an undisturbed soil. Therefore one must use a great deal of caution in interpreting triaxial test data as well.

It should be made perfectly clear that an in-place field vane test should not necessarily duplicate the results of triaxial tests. In-place vane tests give a measure of the in-place undrained shear strength in a vertical direction of a clay. Stratification, shells, fissures, and sand seams may all affect the values obtained, but these effects should be considered and interpreted in using the results. The same factors should be considered in any other type of test.

In conclusion, the vane test can be said to give consistent, easily obtained in-place shear strength of soft and medium clays. The results are open to interpretation, and should never be obtained without sampling and identification of soils or without running other types of tests. The fact that the tests are made under as close to the existing natural conditions with the least disturbance possible, is a great advantage over other types of shear tests. Certainly more research is needed concerning actual stress conditions during failure and the effect of the rate of straining on strength. The vane test belongs with the other tests as another important tool, and should be employed wherever it can be used to advantage.