DISCUSSION

ROBERT L. KONDNER[1]—The review of the various aspects of the strength and resistance of cohesive soils under applied stresses given by Schmertmann is a very interesting study in contrasts. Although the writer agrees with many of the points reviewed by Schmertmann, there are many points of disagreement.

Although he uses several parameters such as D_ϵ and I_ϵ or the previously used parameters, c_e or ϕ_e, in considering shearing resistance, Schmertmann is actually dealing with the stress-strain aspect of the stress-strain-time response of cohesive soils. In studying material behavior it is important, if possible, to express the response in terms of the fundamental variables under consideration, which in this case are stress, strain, and time, or in terms of parameters that are directly defined or calculated from them rather than artificial or indirect parameters. Schmertmann is attempting to study stress-strain-time behavior using the techniques or methods of representation used for studies of ultimate strength or failure stresses. Such techniques, as used by Schmertmann, are not compatible with material behavior at strains below failure.

The most widely used formulations of ultimate or failure strength of soils have their basis in the modified Mohr-Coulomb criterion expressed as a failure envelope in a two-dimensional stress space. This failure criterion concept does not refer to or correlate with the strain space; that is, it does not provide a relationship which specifies the coaxiality or orientation of the stress tensor relative to the strain tensor; nor does it provide a basis for an equational relation between them. The so called "cohesion" and "angle of internal friction" are fictitious soil properties which in reality are simply expedient parameters that have been used to approximate the representation of the failure envelope. It is indeed unfortunate that the names "cohesion" and "internal friction" were ever given to these parameters which are an "intercept" and a "slope," respectively, of an empirical curve fit. This has been recognized by some people for a long time and has been ably expressed by Lambe.[2]

In terms of failure stresses or shear strength in the plane of failure at the time of failure, for use in a form of limit or ultimate analysis, these two empirical parameters are useful engineering indices. However, there is no theoretical basis for extending the failure envelope concept to various stress-strain states below failure because strains at such stress states are not unique but are functions of the history or loading path of the soil up to the stress state as well as the nonlinear viscoelastic nature of the soil. Schmertmann seems to indicate a vague awareness of this at various points in his paper but then proceeds to ignore it by

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[2] T. W. Lambe, "The Engineering Behavior of Compacted Clay," *Proceedings*, Am. Soc. Civil Engrs., Paper No. 1655, Vol. 84, No. SM2, 1958, p. 1655–20.

perpetuating the use of artificial parameters in introducing the quantities, D_ϵ and I_ϵ. The fact that there is a soil resistance to the applied loads or deformations is beyond question, but to divide this resistance into various parts with associated mechanisms of behavior is purely speculative and subject to considerable question. In addition, it would be highly unlikely for a number of investigators to agree on basic definitions and importance of any parts of such a division. The use of artificial parameters instead of fundamental variables can be very misleading in attempting to explain the stress-strain-time response of soils and, hence, is not to be recommended. This does not mean that all such parameters have no use as engineering indices for particular situations. In the future it might well be advisable for Schmertmann to consider stress-strain-time response of soils in terms of the fundamental quantities under consideration, namely, to express his results in terms of stress, strain, and time directly, in addition to the path and history variables.

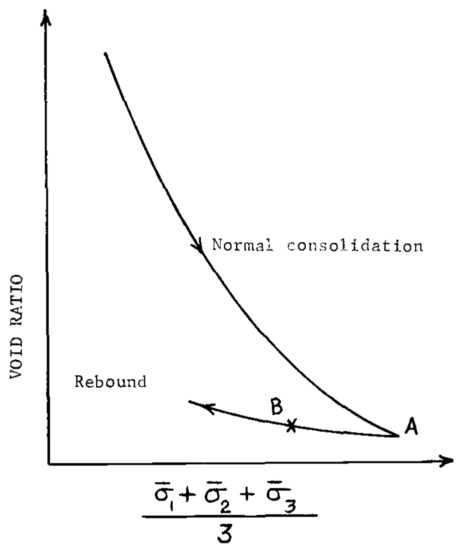

FIG. 5—Void Ratio-Pressure Relation.

The writer agrees with Schmertmann's contention that, in general, void ratio alone is not sufficient to describe the "state" of a soil. The term "state" may contain a variety of effects including such items as path dependence, history, and structure. The CFS or IDS test developed by Schmertmann is certainly an ingenious test and may prove to be a very valuable experimental tool for the soil mechanician. This may be particularly true in light of the difficulty of trying to obtain a number of genuinely identical soil specimens. However, the manner in which the test is conducted using one specimen with the curve-hopping technique is such that the instantaneous effective mean hydrostatic stress is continually changing; hence, one is continually operating on a portion of the recompression branch of the void ratio-pressure relation. This is shown qualitatively in Fig. 5, in which the test specimen is hydrostatically consolidated to point A. During the CFS curve-hopping test, the effective hydrostatic pressure decreases, and one is operating approximately along the recompression path AB. This is a consideration of significant importance. Both in the present paper and in other papers dealing with the CFS test, Schmertmann has indicated that it was possible to obtain approximately the same stress-strain curves for the single specimen with curve hopping as he obtained using a number of individual test specimens. All of these specimens are initially hydrostatically consolidated to the same void ratio as illustrated by point A of Fig. 5. The implication of the validity of the curve-hopping technique is an implication of the validity of the principle of superposition of effects, that is, linearity of effects. It is important to realize in making the substitution of one specimen for a number of specimens that all are related or associated with the vicinity of a single region of the e-p space such as the region AB of Fig. 5. For such a situation, the overconsolidated nature of the soil for the recompression branch would indicate that in general the test is being completely conducted on a portion of an unloading curve with strain-hardened effects built into the soil structure; and, hence, one should expect a quasi-linear behavior. It is well known that the general principle of superposition does not hold for soils.[3] Indications are that the curve-hopping technique is valid only for small variations in the loading history of a soil. Thus, one must ascertain the effects of "slight" changes in the stress and deformation paths both before and during the test. Although Schmertmann states that void ratio alone is not sufficient to describe structural effects in soil response, he uses it as an indication of structural change and notes that the void ratio variation is less than one per cent. Thus, the extent of the general applicability of the CFS test, and the curve-hopping technique remains to be shown. Of equal importance is the form in which the test results are presented and the possible interpretations that are applied to these results.

JOHN H. SCHMERTMANN (*author's closure*)—Mr. Kondner's discussion does not concern itself with the main thesis of this paper, namely, that the I and D components can be considered generalizations of the Hvorslev effective components. Presumably he has no opinion about, or agrees with, this thesis. He does question in some detail the significance of the I and D components and the test technique to determine them. By implication he is also questioning the Hvorslev effective components.

For the purpose of efficient discussion I take the liberty of offering this concise restatement of Kondner's criticisms: (1) My omission of consideration of time, which is an important variable. (2) My perpetuation of cohesion and friction philosophy, which he considers to be nonfundamental. (3) In his opinion the use of Mohr circles for separation of components at strains less than failure is theoretically unjustified. (4) He sees this paper as implying the validity of superposition in soils, and he disagrees. I shall discuss these in this order.

1. One cannot but agree that time is an important independent variable. However, to simplify the main thesis of the paper I noted that methods of testing were to be considered constant. This was intended to be interpreted in the broad sense of including sample storage time, strain rate or rate of stress application, and any other time-dependent effect. I believe that a useful experimental approach toward a better understanding of the mechanism of shear resistance in soils is to consider stress-strain, strain-time and stress-time individually with the time, stress, or strain (respectively) held constant. This paper deals with stress-strain.

The generalized components can be, and have been, evaluated as functions of various time effects. Already published examples are Bea's (**20**)[4] study of creep (strain-time), the studies of creep and relaxation (stress-time) by Wu *et al.* (**15**), and Schmertmann and Hall's (**21**) study of creep and rate-of-strain (in closure).

2. Kondner seems to have missed the essential difference between the "intercept" and "slope" parameters obtained from the empirical straight line fit to approximate the Mohr failure envelop over the range of stress interest, and the generalized effective stress parameters I_ϵ and D_ϵ. With the *IDS* test the soil structure remains comparatively much more con-

[3] K. Terzaghi, *Theoretical Soil Mechanics*, John Wiley and Sons, New York, 1943, pp. 394–395.

[4] The boldface numbers in parentheses refer to the list of references appended to the paper.

stant per unit change in effective stress. Parameters I and D are measures of a soil's shear resistance sensitivity at a given structure to a probing, seemingly nondestructive change of effective stress. This must be contrasted to the ordinary "cohesion" and "angle of internal friction" terms which represent the strength parameters from tests usually encompassing a large range in effective stress, with the different tests involving different failure modes, dilatancy behavior, failure strains, and void ratio at failure—in short, greatly different structure. The I_ϵ and D_ϵ symbols are used to help avoid missing this point.

It is clear from the history of soil mechanics that a great surge in our understanding of the engineering behavior of soils occurred with Terzaghi's laboratory and field demonstrations of the importance of effective stress. It is also clear that because soil deformation results primarily from sliding between particles the shear resistance of soil is fundamental to all shear and consolidation problems. Consequently, it is my opinion that the shear resistance sensitivity of a given soil structure to a change in effective stress, and the change of this sensitivity with strain, are of fundamental importance. I developed the *IDS* test as a practical means of determining this sensitivity.

3. The Mohr stress circle is simply a graphical representation of the distribution of shear and normal stress on any plane in a two-dimensional stress field, or where two of the principle stresses have the same magnitude. Static equilibrium is assumed—which is approximately true at all times with conventional rates of strain. The less the strain the more closely it is true because of reduced creep effects. At any strain, such as a strain less than failure, the two Mohr circles obtained from an *IDS* test permit a simple determination of how the normal stress and shear resistance on any plane changed in response to an imposed change in the effective stress conditions. The I and D components express this change, quantitatively, for that (any) plane.

The theoretical justification for the above use of the Mohr circles is as sound, and perhaps more so because of reduced creep, as that for their use at a defined "failure" condition. Confusion due to concern with stress history and time effects is unnecessary, because the generalized components are determined for the condition of the soil as found at the instant of the imposed effective stress change. As mentioned, stress history and time effects can be and have been studied independently.

The common procedure[5, 6] of indicating the progress of a triaxial test by means of stress paths assumes the validity of the use of the Mohr stress circle representation throughout the test. To my knowledge, this assumption has not been questioned previously in written discussion. This is a good assumption, with a degree of validity much greater than most assumptions made in soils engineering.

4. The experimental success of the curve-hopping procedure is a fact which the reader can verify (**17**). However, from this the author makes no implication of the validity of superposition or linear elasticity in soils. This implication is made by Kondner and he then argues against it.

Without here supporting the possible applicability of superposition, Kondner's

[5] A. Casagrande, and S. D. Wilson, "Prestress Induced in Consolidated-Quick Triaxial Tests," *Proceedings* of the Third International Conference on Soil Mechanics and Foundation Engineering, Switzerland, 1953, Vol. 1, p. 106, 1953.

[6] T. W. Lambe, "Methods of Estimating Settlement," *preprint* submitted to the American Society of Civil Engineers Conference on The Design of Foundations for the Control on Settlements, Session 1, Evanston, Ill., June, 1964.

argument against it is weakened by his choice of reference. On the pages cited Terzahgi said essentially (in 1942) that superposition is not valid for the case of layered systems in which each layer has a different modulus. Curtis and Richart[7] showed in 1955 that it was valid for this case.

Referring to the success of curve hopping, I stated "Either very little structural change occurs with each hop or the shear resistance effects of any change are almost recoverable with continued strain." If the latter (partial collapse of soil structure, recovery with strain, partial collapse, etc.) explanation is correct, then the soil's seemingly elastic behavior is only a superficial observation.

Mention of void ratio change during a single curve hop serves two purposes. The small magnitude of this change is a necessary, though of course not a sufficient, condition for indicating a small change in structure. However, it should be remembered that the main thesis of the paper is the relationship between the Hvorslev and *IDS* effective components and that the Hvorslev components are determined with no change in void ratio. To compare with the *IDS* components, wherein a small change in void ratio is permitted, it was considered useful to indicate just how small this change usually is.

[7] A. J. Curtis and F. E. Richart, Jr., "Photoelastic Analogy for Nonhomogeneous Foundations," *Transactions*, American Society of Civil Engineers, Vol. 120, 1955, p. 35.