## DISCUSSION

Κ. V. HELENELUND<sup>1</sup>—George F. Sowers has presented a short and clear review of the methods of strength testing of soils. In his discussion of the direct shear test, he states that an annular or punching direct shear test was proposed for soils by Lambe in 1951. He states that he has used such a test to determine the shear strength of soft rock and he assumes that the test has not been employed elsewhere. It may be interesting to note that a similar punching test was used extensively by the Harbor Board of Gothenburg as early as the 1930s,<sup>2</sup> by the Swedish and Finnish State Railways, and by the Engineering Dept. of the Board of Agriculture in Helsinki.<sup>3</sup> The same apparatus has been used for determining the undrained shear strength of peat, in addition to its use for clays and other typical cohesion soils. A series of punching tests carried out by Tveiten<sup>4</sup> at the geotechnical laboratory of the Finnish State Railways showed the undrained shear strength of sphagnum-peat to be a function of the huminosity, H (degree of decay) of the peat as expressed by the von Post scale shown in Fig. 6; the specimen in the punching test was 4 cm in diam and 1 cm thick.

As regards the history of soil strength testing, the statement "cone penetration tests were used by the Swedish Geologic Inst. in its laboratory as early as 1914" is not quite correct. By "Swedish Geologic Inst." (the same term is also found elsewhere in the text) the author obviously means Swedish Geotechnical Inst. This Institute did not, however, start its activity until 1944. The laboratory cone penetration test was, in fact, introduced by John Olsson, secretary of the Geotechnical Commission of the Swedish State Railways, in 1915.<sup>5</sup>

The ball test may be mentioned in this connection. This test has been used in the USSR for determining the strength properties of frozen soils.<sup>6</sup>

WILLIAM S. HOUSEL<sup>7</sup>—While the program for this meeting is presented as a Symposium on the "Laboratory Shear Testing of Soils," the title of the introductory paper by Professor Sowers, "Strength Testing of Soils," would indicate that the discussion is not limited to the laboratory. It leaves room to point out that the objective of all soil testing must be the determination of strength under field conditions, the nature of which may preclude duplication in the laboratory. Peck and Lowe, among

<sup>&</sup>lt;sup>1</sup> Professor, Finland Institute of Technology. <sup>2</sup> B. Fellenius, "Apparatus for Determining the Shear Strength of Clays," *Teknisk Tidskrift*, No. 4, Stockholm, 1938.

<sup>&</sup>lt;sup>3</sup> K. V. Helenelund, "Stability and Failure of the Subsoil," State Institute for Technical Research, Publication No. 24, Helsinki, 1953; U. Airaksinen, K.-H. Korhonen, and M. Ware, "On the Strength Characteristics of Soil in Hydraulic Engineering Projects," Soil and Watertechnical Investigations, No. 94, Board of Agriculture, Helsinki, 1961.

<sup>&</sup>lt;sup>4</sup> A. Tveiten, "Geotechnical Investigations of Peat," thesis, Norwegian Institute of Technology, Trondheim, 1954.

<sup>&</sup>lt;sup>5</sup> L. Bjerrum and N. Flodin, "The Development of Soil Mechanics in Sweden 1900-1925," *Geotechnique*, No. 1, 1960.

<sup>&</sup>lt;sup>6</sup> N. A. Tsytovich, "The Fundamentals of Frozen Ground Mechanics," *Proceedings*, International Conference on Soil Mechanics, Vol. 1, London, p. 116.

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others, expressed this view very well in the following excerpt from their Moderators' Report on the "Shear Strength of Undisturbed Cohesive Soils" at the 1960 Am. Soc. Civil Engrs. Research Conference on Shear Strength of Cohesive Soils in Colorado:

"It seems apparent that there are numerous

an inclination to feel that the really fundamental research on shear strength of undisturbed soils must be done in the laboratory, and that the results of the laboratory studies may be applied to field conditions with a minimum of evidence to support the extrapolation. The panel discussions have indicated that there may be dangerous pitfalls in this path."



FIG. 6—Undrained Shear Strength, Determined by Punching Tests, of Sphagnum Fuscum Peat as a Function of the Huminosity of the Peat.

unanswered questions with regard to the shear strength of undisturbed soils. Many of these arise because of doubts regarding the applicability of laboratory findings to field conditions. It is recognized that the mere act of obtaining a sample from a natural deposit radically alters the state of stress and induces strains, and that natural deposits are rarely homogeneous. Yet there seems to be

#### FIELD LOADING TESTS

Rather than going from the laboratory to the field, the reverse sequence was adopted in the research program initiated by the University of Michigan in 1927. Faced with the immediate necessity of furnishing information to the design engineers of the structures which provided the opportunity for investigation to be made, field loading tests were adopted as the most direct and promising approach to the problem. It was recognized at the time that there was much criticism of field loading tests, leading to a widely circulated view that they were unscientific and unreliable. After a review of then current writing, it was concluded that the unsatisfactory experience with such tests was primarily due to the fact that most tests had not been conducted in a scientific manner and their limitations had not been carefully assessed in practical application of the results.

There is not time in this discussion to repeat the detailed development of field loading tests in the Michigan research program. This development, including the use of test results in foundation design, has already been described several times in readily available publications and was last thoroughly documented in 1959 in the ASTM Symposium on Time Rates of Loading in Soil Testing.<sup>8</sup> The story of field loading tests and the transition from the field to the laboratory will be sketched very briefly here, presenting the facts most pertinent to the present discussion.

For the first five years, from 1927 to 1932, the major emphasis was on field loading tests, although work on field penetration observations and a direct shear test was being carried on concurrently. The significant results of this early investigation were incorporated in the linear equation for bearing capacity identified with the Michigan program. In this equation soil resistance was expressed in terms of the two basic stress reactions developed by the loaded soil, which were designated "developed pressure" and "perimeter shear." The validity of this linear equation as a quantitative representation of measured test results has been demonstrated many times. Actual settlement of spread footings designed within the static resistance of the soil as determined by field loading tests has been consistently close to that predicted from the tests; results of this experience have been published.

Field loading tests and the perimeterarea relationship were used by McLeod in his evaluation of the supporting capacity of airfield pavements for the Canadian Department of Transport in 1945-1946.9, 10 The methods of evaluation developed at that time have been extended and are still the primary basis of design procedure for flexible pavements used by the Department of Transport, as indicated in the following quotation.<sup>11</sup> The Special Committee on Pavement Design and Evaluation of the Canadian Good Roads Association has also adopted these methods and correlated load test results with Benkelman Beam deflections.<sup>12, 13</sup>

"The Department of Transport flexible pavement design was developed on the basis of plate load testing of existing fields...

<sup>11</sup> G. Y. Sebastyan, "Flexible and Rigid Pavement Design Procedure," Canadian Dept, of Transport, Construction Branch, Airport Development, Engineering Design, (department report) 1960.

<sup>12</sup> E. B. Wilkins, "Method of Design for Strengthening Existing Pavements," *Proceedinggs*, Forty-first Convention of the Canadian Good Roads Association, Ottawa, Ontario, Canada, 1960.

<sup>13</sup>G. Y. Sebastyan, "The Benkelman Beam Deflection as a Measure of Pavement Strength," Pavement Design and Evaluation, Preprint of Proceedings, Forty-first Convention of the Canadian Good Roads Association, Ottawa, Ontario, Canada, 1960.

<sup>&</sup>lt;sup>8</sup> W. S. Housel, "Dynamic and Static Resistance of Cohesive Soil-1846-1958," Soils, ASTM STP 254, Am. Soc. Testing Mats., 1960.

<sup>&</sup>lt;sup>9</sup> N. W. McLeod, "Airport Runway Evaluation in Canada," Highway Research Board, *Research Report No. 4-B*, Washington, D. C., 1947.

<sup>&</sup>lt;sup>10</sup> N. W. McLeod, "A Canadian Investigation of Load Testing Applied to Pavement Design," Load Tests of Bearing Capacity of Soils, ASTM STP 79, Am. Soc. Testing Mats., 1948.

(ASTM D 1195 – 57),<sup>14</sup> the subgrade being at equilibrium moisture condition.

"The major variables were evaluated by Dr. N. W. McLeod and reported in Highway Research Board proceedings...

"The basic variables are as follows:

"a. Perimeter-Area Ratio and Load Carrying Capacity at a given deflection. A straight line relationship was obtained between the pressure carried at any given deflection at various perimeter-area ratios. This follows the principles established by Professor W. S. Housel of the University of Michigan and later confirmed by the British Air Ministry in the load classification number study...

"b. Deflection and Load Repetition. The relationship between deflections and load repetitions was established . . . It is a straight line on a semilogarithmic scale. This relationship was confirmed by repetitive triaxial testing by Professor Meyerhof of the Nova Scotia Technical College . . .

"c. Seasonal Load Carrying Capacity. All the load testing was done during the summer period between July and October when the load carrying capacity of the subgrade does not change appreciably. In design the spring condition should be taken into consideration, as in spring the subgrade load-carrying capacity is at a minimum."

Hicks adopted the same procedures in the design of highway pavements in North Carolina, where they have been successfully applied for many years.<sup>15, 16</sup> A number of investigators representing various agencies have used field loading tests successfully to determine the supporting capacity of pavements including, in addition to those cited above, the U.S. Bureau of Public Roads, the Civil Aeronautics Administration, U. S. Navy Department, U. S. Corps of Engineers, and several private agencies. A comprehensive documentation of this work has been assembled in the Symposium on Load Tests of Bearing Capacity of Soils conducted by ASTM Committee D-18 in 1947.<sup>17</sup>

Perhaps the most comprehensive series of field loading tests was that conducted by the Highway Research Board at Hybla Valley, in an investigation of flexible pavements extending over a period of some 12 years (from 1946 to 1958), reported in 1959.<sup>18</sup> This work can be cited as another demonstration of the reliability of the linear equation for bearing capacity in reproducing test results. Ingimarsson measured showed that in 89 tests on 26 different flexible pavement sections and all combinations of plate size up to a diameter of 30 inches, 92 per cent of the test results fell within  $\pm 5$  per cent of values computed by the equation and 99.6 per cent were within  $\pm 10$  per cent.<sup>19</sup>

The most widespread use of field loading tests has taken place during and since the Second World War under the impetus of accelerated airfield and highway construction programs. It is interesting to note that this successful practice has developed in connection with pavement design, involving layered systems in which the stress reactions mobilized in the pavement and supporting soil are much more complex than in building foundations which may more generally be treated as a single supporting medium.

This situation would appear to empha-

<sup>&</sup>lt;sup>14</sup> Method for Repetitive Static Load Test of Soils and Flexible Pavement Components for Use in Evaluation and Design of Airport and Highway Pavements, 1964 Book of ASTM Standards, Part 4.

<sup>&</sup>lt;sup>15</sup> L. D. Hicks, "Current Base Design Practices in North Carolina," *Proceedings*, Highway Research Board, Vol. 26, Washington, D. C.. 1946.

<sup>&</sup>lt;sup>16</sup> L. D. Hicks, "Flexible-Pavement Design as Revised for Heavy Traffic," Highway Research Board, *Research Report 16-B*, Washington, D. C., 1954.

<sup>&</sup>lt;sup>17</sup> Load Tests of Bearing Capacity of Soils, ASTM STP 79, Am. Soc. Testing Mats., 1948.

<sup>&</sup>lt;sup>18</sup> "A Cooperative Study of Structural Design of Nonrigid Pavements—Review of Test Procedures and Presentation of Rigid Plate Bearing Test Data," Highway Research Board, *Special Report 46*, Washington, D. C., 1959.

<sup>&</sup>lt;sup>19</sup> G. R. Ingimarsson, "An Analysis of Hybla Valley Rigid Plate Bearing Data," Highway Research Board, *Bulletin 289*, Washington, D. C., 1961.

size the practicability and reliability of the field testing procedures that have been developed over the years. It seems significant that practicing engineers resorted to this direct and realistic approach to the problem when faced with directly correlated with shear testing of soils in either the field or laboratory, it is the primary objective of the present discussion to bring this subject once again to the attention of those interested in soil testing.



FIG. 7-Stress Reactions in the Compression Cone.

the necessity of producing results under the critical construction programs of this period. The writer has always been puzzled by the reluctance and, on the part of some investigators, the persistent refusal to recognize the older and equally valid application of these methods of evaluating soil bearing capacity under field conditions in the design of building foundations. Inasmuch as it is in connection with building foundations that field loading tests can be most

# Developed Pressure or Triaxial Compression:

The stress reactions developed by a soil mass under field loading conditions, as defined in the linear equation for bearing capacity, were first presented in a discussion of a paper by Terzaghi in 1928 in the ASCE *Proceedings.*<sup>20</sup> It was

<sup>&</sup>lt;sup>20</sup> W. S. Housel, Discussion of "The Science of Foundations—Its Present and Future," *Transactions*, Am. Soc. Civil Engrs, Vol. 93, 1929; *Proceedings*, April, 1928.

shown that developed pressure or triaxial compression, the major source of bearing capacity in large bearing areas, was neglected by the "Diameter Rule" presented by Terzaghi as a fundamental principle of foundation engineering. Mathematically, it was demonstrated that this widely accepted generalization was equivalent to postulating that the load on a bearing area was carried entirely at the edge of the area by resistance associated with lateral distribution of applied pressure, which the writer had defined as perimeter shear.

The complete concept of bearing capacity describing the relationship between developed pressure and perimeter shear and the shearing resistance of cohesive soils is shown in Fig. 7, as presented in 1935 at the Georgia Institute of Technology at a metting of the Society for Promotion of Engineering Education. This presentation was subsequently published in the ASCE *Proceedings* as a discussion of a paper by Cummings entitled "Distribution of Stresses Under a Foundation".<sup>21</sup>

Fig. 7 shows the increments of pressure developed as shearing resistance is mobilized by mutually supporting elements of mass within the compression cone. The first increment,  $n_1$ , is associated with lateral distribution of applied load on the boundary of the loaded central column, the limit of which is the maximum shearing resistance on the perimeter planes. Further pressure increments are developed as a concentration of pressure within the central column and transmitted downward without lateral distribution. The limit of this resistance is set by the shearing resistance of the soil in increments that can be identified as: (1) the unconfined compressive strength of the primary element the maximum deviator stress in or

<sup>21</sup> A. E. Cummings, "Distribution of Stresses Under a Foundation," *Transactions*, Am. Soc. Civil Engrs, Vol. 101, 1936. triaxial compression,  $n_2$ ; (2) the lateral confining pressure limited by the maximum difference in principal pressure on secondary elements outside the central column; and (3) the surcharge pressure transmitted through the mass as a flotation effect.

As a matter of theory, the fundamental principles involved are the application of the laws of static equilibrium to a system of elements of mass in a soil which fails in shear on planes of maximum shearing stress at 45 deg to the assumed principal planes. There are some simplifying assumptions made to avoid the complications of curved surfaces of failure and angles of pressure transmission. On the other hand, the simplified block elements permit the evaluation of dimensional effects associated with the soil stratification and applied load concentration that cannot be incorporated in mathematical developments sometimes considered to be more rigorous. Finally, the validity of such a treatment must depend on the accuracy with which the linear equation reproduces test results, demonstrations of which have already been presented.

The linear equation for bearing capacity holds for constant settlement as the size of bearing area varies. A general equation for settlement was developed in 1929, with soil resistance coefficients essential to evaluating the magnitude and sequence of development of the stress reactions at variable settlement.<sup>22, 23</sup> The soil resistance coefficients were formulated in terms of settlement and stress reactions, which were measurable quantities under field loading

<sup>&</sup>lt;sup>22</sup> W. S. Housel, "A Practical Method for the Selection of Foundations Based on Fundamental Research in Soil Mechanics," *Engineering Re*search Bulletin No. 13, University of Michigan, Ann Arbor, Mich., 1929.

<sup>&</sup>lt;sup>23</sup> W. S. Housel, "Research in Foundations and Soil Mechanics," Final Report of the International Association for Bridge and Structural Engineering, Verlag von Wilhelm Ernst and Sohn, Berlin, 1939.

conditions and replaced the conventional physical constants not quantitatively determinate. The theoretical relationship between the soil resistance coefficients and stress reactions in the general equation for settlement and those physical quantities more frequently used in evaluating strength of materials were subsequently presented in a generalized theory of soil resistance.24 Included in this comparison were the coefficient of compressibility, the modulus of incompressibility or modulus of elasticity in compression, the modulus of rigidity, Poisson's ratio, the angle of pressure transmission, and the depth to which finite pressure is transmitted.

As a matter of terminology, the writer has always felt that developed pressure is a more descriptive term than triaxial compression, not only conveying the idea of pressure or cubical compression but also implying that the pressure has been developed under field loading conditions. By persistent effort, the writer was able to have the stress reactions, developed pressure and perimeter shear, included in standard nomenclature originally worked out by the joint committee of ASTM and ASCE,<sup>25</sup> and was disappointed when these terms were subsequently eliminated by the reorganized committee in 1958 over the writer's protest. Consequently, they are no longer in the ASTM Standard.<sup>26</sup>

#### LABORATORY SHEAR TESTING

Field loading tests, when conducted on a sufficient number of plate sizes and with proper control of all test conditions, are both time-consuming and expensive. For this reason it is highly desirable to develop laboratory tests to measure the soil resistance factors which control capacity under field conditions. After some five years, starting in 1927, emphasis in the Michigan research program shifted from the field to the laboratory, as it was felt that the essential elements of "in place" capacity had been established.

In 1933, Donald S. Berry as Detroit Edison Research Fellow undertook a comprehensive investigation of soil resistance in the Soil Mechanics Laboratory at the University of Michigan and pursued this program for two years. Based on previous field experience, this phase of the study was concentrated on a direct shear test and a stabilometer test to duplicate the developed pressure stress reaction.

### Direct Shear and Unconfined Compres sion:

The ring shear test selected as a direct shear test was suggested in earlier work by Bell in England.<sup>27</sup> It was used pririly to measure shearing resistance of cohesive soils which, by generally accepted definition, permits testing at zero normal pressure to isolate cohesion. The essential changes made in the ring shear test that made it successful in dealing with cohesive soils in practice were the elimination of normal pressure and the introduction of increment loading at constant time intervals. The latter change made it possible to measure rates of deformation with time held constant, and then extrapolate these rates to zero and determine the yield value or static resistance as originally defined by Maxwell.

Sufficient data were accumulated by 1935 to establish a satisfactory correlation between shearing resistance, field

<sup>&</sup>lt;sup>24</sup> W. S. Housel, "A Generalized Theory of Soil Resistance," *Papers on Soils, ASTM STP* 206, Am. Soc. Testing Mats., 1957.

<sup>&</sup>lt;sup>25</sup> Terms and Symbols Relating to Soil Mechanics, (D 653-42 T), 1942 Book of ASTM Standards, Part 2.

 $<sup>^{26}</sup>$  Definitions of Terms and Symbols Relating to Soil Mechanics, (D 653-64) 1964 Book of ASTM Standards, Part 11.

<sup>&</sup>lt;sup>27</sup> A. L. Bell, "The Lateral Pressure and Resistance of Clay," *Proceedings*, Institute of Civil Engineers (London), Vol. 196, 1914-15.

penetration observations, and the stress reactions developed in field loading tests.<sup>28</sup> More extensive correlations have subsequently been possible, including comparative test results from the widely used unconfined compression test following a procedure introduced by Terzaghi and Peck.<sup>29, 30</sup> Since 1942, the Soil Mechanics Laboratory at the University of Michigan has run these two tests in parallel on all specimens. Comparative test results are now available on more than 30,000 individual specimens and provide a broad base for the correlation of the static shearing resistance or yield value and the dynamic increase in the ultimate shearing resistance involved in the unconfined compression test.

The ratio between these two shear values has consistently been found to be 4:1 for purely cohesive soils; in the case of granular-cohesive mixtures, the ratio varies. The relationship between the shear values from these two types of test, the safety factors recommended by Terzaghi and Peck, and the overload ratios used by the writer have been generally recognized and understood.<sup>31, 32</sup>

#### Triaxial Compression Test:

As previously noted, the Michigan stabilometer was designed to measure directly the components of developed pressure identified as one of the stress reactions in the linear equation for bearing capacity. A device for measuring pressure in these terms was independently conceived as part of the laboratory testing program in which Berry was engaged. The earliest model of the stabilometer, designed in 1934, was subsequently modified to provide for testing specimens over a larger range of heightdiameter ratios. The earliest reference to this equipment in the published literature was in 1935.<sup>33</sup> The Hyeem stabilometer and independent development of a similar test for soils by Rendulic and Buisman in Europe have been documented in the literature.

Haythornthwaite in his review of the development of triaxial testing found the Michigan tests to be the first conducted in this country with positive control of lateral pressure.<sup>34</sup> In this respect he touched upon a significant point in test procedure required to measure the ultimate capacity of a soil mass to sustain a pressure differential. This fundamental difference between Hveem's test procedure and positive control of lateral pressure was commented on by the writer in 1936.<sup>35</sup>

Berry's investigation and thesis were completed in early 1936 and presented the results of three comprehensive series of tests on five different granular materials in a state approaching maximum consolidation. Granular materials were selected for several reasons: first, the ring shear and unconfined compression tests were considered best suited to measure cohesion; second, they afforded greater reproducibility in texture and density in test specimens, necessary for compara-

<sup>&</sup>lt;sup>28</sup> W. S. Housel, "A Penetration Method of Measuring Soil Resistance," *Proceedings*, Am. Soc. Testing Mats., Vol. 35, 1935.
<sup>29</sup> R. B. Peck, "Earth-Pressure Measure-

<sup>&</sup>lt;sup>29</sup> R. B. Peck, "Earth-Pressure Measurements in Open Cuts, Chicago (Ill.) Subway," *Transactions*, Am. Soc. Civil Engrs, Vol. 108, 1943.

<sup>&</sup>lt;sup>30</sup> K. Terzaghi, "Liner-Plate Tunnels on the Chicago Subway," *Transactions*, Am. Soc. Civil Engrs, Vol. 108, 1943.

<sup>&</sup>lt;sup>31</sup> G. P. Tschebotarioff, Soil Mechanics, Foundations, and Earth Structures, McGraw-Hill Book Co., Inc., New York, 1951. <sup>32</sup> W. S. Housel, "Field and Laboratory Cor-

<sup>&</sup>lt;sup>22</sup> W. S. Housel, "Field and Laboratory Correlation of the Bearing Capacity of Hardpan for Design of Deep Foundations," *Proceedings*, Am. Soc. Testing Mats., Vol. 56, 1956.

<sup>&</sup>lt;sup>33</sup> D. S. Berry, "Stability of Granular Mixtures," *Proceedings*, Am. Soc. Testing Mats., Vol. 35, Part 2, 1935.

<sup>&</sup>lt;sup>34</sup> R. M. Haythornthwaite, "Mechanics of the Triaxial Test for Soils," *Journal of the Soil Mechanics and Foundation Division, Proceedings*, Am. Soc. Civil Engrs., Vol. 86, October, 1960.

<sup>&</sup>lt;sup>35</sup> W. S. Housel, "Internal Stability of Granular Materials," *Proceedings*, Am. Soc. Testing Mats., Vol. 36, 1936.

tive analysis; and third, there was need for an independent measure of mechanical stability to combine with shearing resistance due to cohesion in granularcohesive mixtures. The three series of tests were plate-bearing tests on small specimens prepared in the laboratory, direct shear tests under variable normal pressure, and the stabilometer or triaxial compression tests.

Comparative analysis of the test results presented some puzzling inconsistencies which finally led the writer to break away from traditional concepts of resistance predicated on internal friction. Internal stability was defined as the mutual support between particles, controlled primarily by the angle at which the intergranular forces are transmitted and limited by confining pressure or thrust supplied by the mass surrounding the loaded element. The interpretation of test results in terms of this concept has been debated pro and con in the years since it was first presented and is still the subject of frequent discussions.<sup>36</sup>

The crux of the situation was first expressed quite clearly by Terzaghi in 1920,<sup>37</sup> and has been quoted more recently by Rowe.<sup>38</sup>

"The fundamental assumptions of the traditional earth-pressure theories cannot, in fact, stand even superficial examination. The fundamental error was introduced by Coulomb, who purposely ignored the fact that sand consists of individual grains, and who dealt with the sand as if it were a homogeneous mass with certain mechanical properties. Coulomb's idea proved very useful as a working hypothesis for the solution of one special problem of the earth-pressure theory, but it developed into an obstacle against further progress as soon as its hypothetical character came to be forgotten by Coulomb's successors.

"The way out of the difficulty lies in dropping the old fundamental principles and starting again from the elementary fact that the sand consists of individual grains."

Rowe, however, seems to miss the real significance of Terzaghi's statement, as the writer sees it; and for some strange reason, neither Terzaghi nor his proponents have ever followed through to the logical conclusion by actually "dropping the old fundamental principles and starting again from the elementary fact that sand consists of individual grains."

As Terzaghi pointed out in the same article, displacement in a granular mass out of the range of critical density can take place only by volume expansion which is resisted by intergranular pressure. In conclusion, the writer's only further comment would be to ask the following question: What is more logical and realistic than to measure these intergranular pressures directly and avoid the inconsistencies of internal friction which, as Terzaghi puts it, has "developed into an obstacle against further progress"?

G. F. SOWERS (*author's closure*)—Professor Housel rightly points out the importance and value of field or in-place tests. Unfortunately, however, field testing is seriously limited in that the results are applicable to the existing conditions. Unless the test is made under the most critical combinations of environment, however, it may not reflect the soil strength at its poorest (the strength ordinarily needed for design). Furthermore, it is difficult if not impossible in a field test to include the effect of future changes in soil strength imposed by construction. The effects of environment,

<sup>&</sup>lt;sup>36</sup> W. S. Housel, "Interpretation of Triaxial Compression Tests on Granular Mixtures," *Proceedings*, The Association of Asphalt Paving Technologists, Vol. 19, 1950.

<sup>&</sup>lt;sup>37</sup> C. Terzaghi, "Old Earth Pressure Theories and New Test Results," *Engineering News-Record*, Vol. 85, 1920.

<sup>&</sup>lt;sup>38</sup> P. W. Rowe, "The Stress-Dilatancy Relations for Static Equilibrium of an Assembly of Particles in Contact," *Proceedings*, Royal Soc. (London), Series A, Vol. 269, 1962.

and future load changes can be readily studied in the laboratory. In the author's opinion any program of field testing should be correlated with laboratory tests conducted under the full range in loading, water, and environment of the prototype in order to be meaningful. Similarly, no laboratory program of soil testing is complete without field verification by field strength tests or behavior studies of the prototype.

Both Professors Housel and Helenelund have provided valuable additional information on the development of shear testing methods, for which the author is grateful.