LABORATORY SHEAR STRENGTH OF SOIL

A symposium
sponsored by ASTM
Committee D-18 on Soil and Rock for
Engineering Purposes
AMERICAN SOCIETY FOR
TESTING AND MATERIALS

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F. C. Townsend, University of
Florida, editors

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Foreword

The symposium on Laboratory Shear Strength of Soil was held in Chicago, 111., on 25 June 1980. The symposium was sponsored by the American Society
for Testing and Materials through its Committee D-18 on Soil and Rock for Engineering Purposes. R. N. Yong, McGill University, and F. C. Townsend, University of Florida, presided as symposium chairmen and served as editors
of this publication.

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This publication is made possible by the authors and, also, the unheralded efforts of the reviewers. This body of technical experts whose dedication, sacrifice of time and effort, and collective wisdom in reviewing the papers
must be acknowledged. The quality level of ASTM publications is a direct function of their respected opinions. On behalf of ASTM we acknowledge
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STP740-EB/Sep.1981

Introduction

The increasing demand for better means and reliability for prediction of the yield or failure in soils, coupled with the ever present need to provide more realistic generalized stress-strain relationships of soils in design calcu-lations and general analyses, make it very important that the geotechnical engineering profession be provided with an up-to-date appreciation of test techniques for measurement of shear strength and procedures for evaluation and reduction of measurements obtained from relevant test techniques. It has been at least 17 years since the last full documentation and evaluation of laboratory shear strength of soil has occurred {Laboratory Shear Testing of Soils. ASTM STP 361. American Society for Testing and Materials, 1964). There is a need for the profession to re-examine its position on the problems of yield and failure and to document the advances that have been made in the long intervening period in the development of new test techniques and methods for evaluation of the laboratory shear strength of soil.
In the organization of this ASTM Symposium on Laboratory Shear Strength of Soil, advantage has been taken of the fact that two other companion exer-cises have been developed to complement this present study on laboratory test techniques for evaluation of shear strength. The many finer details of plasticity theory and generalized stress-strain relationships have been covered in the NSF/NSERC sponsored Workshop on Plasticity and Gen-eralized Stress-Strain held at McGill University in May 1980, whilst the ap-plication of the theories to generalized practice was presented at an ASCE Symposium in October 1980. This ASTM symposium covers the very much needed study of laboratory techniques for evaluation of shear strength of soil. The object was (a) to meet the requirements for determination and assess-ment of the shearing resistance of soils, (b) to determine the kinds of strength parameters that can be derived from the various test techniques, (c) to assess the relevance of the various techniques presently available, (d) to establish the rationality of the test techniques, and (e) to examine the viability of the various models used for data reduction and the methods of application of data and measurements for assessment of shear strength of soils.
There have been great advances made not only in equipment and instru-mentation, but also in methods of tests and degree of sophistication of test
techniques. In addition, advances have been made in methods of analysis,
particularly with reference to the application of the measurements.
The symposium was developed as a two-session presentation, each session

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LABORATORY SHEAR STRENGTH OF SOIL

consisting of a state-of-the-art report and panel presentation. The program format and participants are given as follows:

Session I—Strength Testing Methods and Requirements

Chairman
State-of-the-Art
Speaker
State-of-the-Art
Report

E. T. Selig, University of Massachusetts at Amherst
A. S. Saada, Case Western Reserve University, Cleveland

A. S. Saada, Case Western Reserve University, Cleveland, and F. C. Townsend, University of Florida, Gainesville

Panel Discussion

Moderator
Panelists

F. C. Townsend, University of Florida, Gainesville
C. C. Ladd, Massachusetts Institute of Technology, Cam-
bridge
P. LaRochelle, Laval University, Quebec City
S. Wright, Texas University at Austin
S. Poulos, Geotechnical Engineers, Inc., Winchester, Mass.

Session II—Data Reduction and Application of Measurements for Analytical Modeling

Chairman
State-of-the-Art
Speaker
State-of-the-Art
Report

E. T. Selig, University of Massachusetts at Amherst
H. Y. Ko, University of Colorado at Boulder

H. Y. Ko and S. Store, University of Colorado at Boulder

Panel Discussion

Moderator
Panelists

R. N. Yong, McGill University, Montreal
F. Tavenas, Quebec City
J. H. A. Crooks, Golder Associates, Mississauga, Ontario
George Y. Baladi, Waterways Experiment Station, Corps of
Engineers, Dept. of the Army, Vicksburg, Miss.
R. J. Krizek, Northwestern University, Evanston, III.

The contributions made by these participants and by the audience are gratefully acknowledged. The papers submitted to the symposium were divided into the two sessions, and were examined, evaluated, and discussed as part of the session presentation. These papers are organized in this STP as they appeared in each session. They provide the extension of the various test techniques and methods of analyses to specific examples of tests for various problem soil materials, new test techniques and applications, and particular
methods of application of data reduction and evaluation. They serve as a
means for demonstrating the wide range of applicability of test measure-
ments and techniques. The editors also acknowledge the input and assistance

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INTRODUCTION

provided by Professors H. Y. Ko, K. Y. Lo, H. W. Olsen, A. S. Saada, and

E. T. Selig, who functioned as an ad hoc Task Committee.

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Strength Testing Methods
and Requu^ments

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A. S. Saada^ andF. C. Townsend^

State of the Art: Laboratory Strength Testing of Soils

REFERENCE: Saada, A. S. and Townsend, F. C, "State of the Art: Laboratoiy Strength Testing of Soils," Laboratory Shear Strength of Soil. ASTM STP 740. R. N. Yong and F. C. Townsend, Eds., American Society for Testing and Materials, 1981, pp. 7-77.

ABSTRACT: A review and evaluation of the advantages and limitations of laboratory equipment for measuring the shear strength of soils are presented. Equipment evaluated include direct shear, torsional shear, simple shear, triaxial, multiaxial (true triaxial), plane strain, hollow cylinder triaxial, and directional shear devices. The evaluation in-dicates that the impetus to obtain parameters for constitutive equations and modeling has resulted in the development of improved equipment and testing techniques; specifically, the development of multiaxial (true triaxial) and hollow cylinder triaxial test equipment. Although these devices are more versatile, the conventional solid cylinder triaxial test is still the most popular. The evaluation suggests that direct shear and simple shear devices are best utilized by designers who have gained experience applying the results from such tests to structures that have behaved satisfactorily.
Proper consideration must be given to the effects of membrane penetration, end restraint saturation and consolidation procedures, and rates of loading in any testing pro-gram.

KEY WORDS: soils, shear strength, laboratory testing equipment, triaxial tests, direct shear, simple shear, torsional shear, hollow cylinder, true triaxial, anisotropy

The object of laboratory testing is to study the behavior of a given soil under conditions similar to those encountered in the field and to obtain those

parameters which describe this behavior in a set of constitutive equations. In a laboratory test the specimen is intended and generally assumed to represent a single point in a soil medium. The validity of this assumption depends on the uniformity of stress and strain distributions within the soil samples. The uniformity will depend on the configuration of the specimen and the control and measurement of stress and strain on its surface. Separate measurements
are often made for the soil phase, the water phase, and sometimes the air

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phase of the specimen in order to relate its contribution to the strength of the mass. While the data needed in design may be less extensive than those re-quired for the development of constitutive equations, the present trend is to obtain as complete a record as possible. Constitutive equations are an in-dispensable ingredient in the application of the finite-element method to geotechnical problems; and the increased availability of computers has resulted in increased pressure for the development of testing equipment capable of covering the whole stress and strain spectra.
Consequently, the last ten years have seen an explosion in the number of tools aimed at better measurements, better recording, and better processing of data obtained during laboratory testing. Testing units conceived many years ago but whose implementation was quite difficult are being used nearly on a routine basis. Automation, both electronic and fluidic, has taken most of the drudgery out of the stressing or straining systems.
In this paper the various apparatuses in operation in soil laboratories for research or routine purposes are reviewed and their advantages and disad-vantages are discussed.
While it is advisable to have a uniform notation and sign convention in a given paper, such a uniformity is difficult to achieve when reference is made to so many publications, each with its own set of conventions. Therefore, when not specifically indicated, the sign convention used in this paper is shown in Fig. 1, where compression is positive and the arrows point in a direction opposite to that used in classical elasticity [1.2].^ For future reference the following definitions are in order [3]:
The term "deviator" is used in conjunction with a state of stress or a state of strain (otherwise known as stress and strain tensors). It is a state in which the trace of the matrix representing stress or strain is equal to zero. In this paper the "difference between principal stresses" (aj — 02, for example) will be called the "principal stress difference".
The term "pure shear", when used with a state of stresses at a point, is a special deviator in which two principal stresses are equal in magnitude and opposite in sign and the third one is equal to zero. Thus (Fig. 2a)

a 0 0

0 -f f 0

0 0 0

represents a state of pure shear. The components here are given in the prin-
cipal system of axes at Point 0. If we now rotate the system of axes by 45 deg
to X-Y and use this new system as our reference (Fig. 2b), the previous matrix becomes

•'The italic numbers in brackets refer to the list of references appended to this paper.

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SAADA AND TOWNSEND ON STATE OF THE ART

0 - T 0'

- T 0 0

0 0 0

Notice that the small square element represents a point through which any plane can pass; on this plane any of the two previous matrices will give the same "stress vector". A state of plane strain is a state in which the three or-thogonal displacements (M, V, and w) are such and u = uix.y), v = vix,y), and w = 0. Such displacements lead to a strain matrix of the form

y.y 0

yxy

0 0 0

The z-direction is a principal direction.
The term "pure shear", when used with relation to a state of strain at a point, is a state of plane strain which consists of a uniform extension in the jc-direction, say, and a uniform contraction in the j^-direction of such an

FIG. 1—Sign convention for stresses.

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(TOO

o-cr 0

O O 0

o -r o

-V o o
0 0 0

FIG. 2—(a) Pure shear stresses at a point; coincident axes: (b) Pure shear stresses at a point; axes rotated by 45 deg.

amount that the volume remains unchanged. In this case (Fig. 3), a rhombus ABCD is distorted under a strain into a congruent rhombus A 'B 'C 'D' in which the acute and the obtuse angles have been interchanged. The three components of the displacement in this case are

u = ex. V —
1 + c

= 0

where c is the strain e^. For small deformations in which c is small compared with unity, it can be neglected in the denominator of the value of v.
The term "simple shear" refers strictly to a state of strain and not to a state of stress. It is a state of plane strain in which the points are displaced only in one direction (parallel to the x-axis, say) such that

M = cy. 0, = 0

where c is the shear strain jj^y shown in Fig. 4. In this case all planes parallel
to the jcz-plane slide in the direction of the x-axis without changing their
distance from each other, and the displacements are proportional to their
distance from the xz-plane. Like the case of pure shear it is a constant

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m

D

/A/IT/AL

^X

F//^AL

l/ = CX

l/^—£- y

FIG. 3—Pure shear strain conditions.

/Nt '7-/> iL.

T

/ i

^1 / / / '/ill
1 1 1 1
f=/A/Al.

U= CV

yv= 0

-X

FIG. 4—Simple shear strain conditions.

volume deformation. Simple shear is equal to pure shear plus a rotation. Finally, it is to be noticed that a uniform state of strain does not necessarily mean that the state of stress is uniform.

A Brief Histoiy of SoU Strength Testing [4a]

It appears that the first real soil shear test was described by Collin in 1846 [4b]. In this test a long specimen of clay 4 cm square in cross section was loaded transversely at its center until it failed in double direct shear (Fig. 5). Leygue in 1885 [5] tilted a shear box full of cohesionless soil until the top slid
across the bottom. It is not known when the direct shear apparatus was in-
vented and if Coulomb, whose formula it uses, had anything to do with it. In
its present form, credited to Krey, Terzaghi, and Casagrande, the direct

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A
FIG. 5—Double direct shear test of Collin [4a].

shear test employs a circular or a rectangular specimen encased in a split box (Fig. 6). A normal force, W, is applied to the top of the box after which a shearing force, 5, forces the top across the bottom, causing the soil to shear along the plane defined by the split between the two parts of the box. The double direct shear test, which seems to be the earliest true shear test for soils [4b], is still in use in its original form [6] or with normal forces applied at its ends (Fig. 7).
The states of stress and strain in the aforementioned direct shear devices are not uniform, and the cross section of soil common to the two parts of the box changes continuously. Torsional direct shear machines with solid and hollow specimens were designed [7] to overcome part of the problem (Fig. 8). The Swedish Geotechnical Institute [8] developed an apparatus where the soil is confined laterally by a rubber membrane and a series of evenly spaced rings (Fig. 9). Roscoe [9] used rigid but hinged plates for the ends of his shear box (Fig. 10); these tilt so as to maintain a constant specimen length parallel to the direction of shear. Peltier [10] introduced a shear box (Fig. 11) with movable sides through which forces can be applied on the intermediate principal plane. The Norwegian Geotechnical Institute (NGI) modified the Swedish device by replacing the rings by a wire embedded in the rubber membrane [11].
Triaxial testing of soils seems to have evolved simultaneously in Germany [12], the Netherlands [13], and the United States [14,15] (Fig. 12). In Ger-many a machine was built at the Prussian Waterways Experimental Station for the purpose of studying the consolidation of clays under conditions of negligible side friction; the surrounding liquid was entirely confined and temperature and leakage had to be closely controlled. Several investigators recognized that the apparatus could be used to measure the ratio of the axial

^

-£E3L
FIG. d—Direct shear test 14a].

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