INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

SUB-SECTION IId

TRIAXIAL TESTS

II d 10 STRESS-DEFORMATION AND STRENGTH CHARACTERISTICS OF SOILS UNDER DYNAMIC LOADS

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SYNOPSIS

This paper describes apparatus developed and results of tests performed to investigate the stress-deformation and strength characteristics of soils under dynamic loads.

INTRODUCTION

In connection with studies of the stability of slopes under the effects of bombing, laboratory investigations on the strength of soils and soft rocks under dynamic loading are being conducted at Harvard University for the Panama Canal.

This investigation is expected to benefit also other engineering problems where soil is subjected to dynamic loading, such as the effects of earthquakes on dams and their foundations, or the effects of transient loading by fast moving traffic on airfield and highway pavements and the underlying materials.

Conventional strength tests on soils are either unconfined compression, or triaxial compression, or direct shear tests. Any of these tests can be performed by means of either a controlled stress or a controlled strain loading apparatus. Loading of the specimen in such tests is performed over a period of at least several minutes. Such tests will be referred to herein as static strength tests, to distinguish them from the dynamic tests described in this paper.

It has been recognized that the strength of soil increases as the rate of loading increases. For example, in connection with the design of the third locks for The Panama Canal, a series of triaxial compression tests were made to determine the strength of a very soft organic clay by producing failure within a range of 1.7 minutes to more than 7 hours. These tests indicate that the strength at the fastest rate of loading was about 40 per cent greater than that at the slowest rate. D.W. Taylor 1) investigated the strength of a clay which was remolded at the liquid limit and then consolidated under 4,22 kg per sq cm. Failure was procuded within the range of 4 minutes to 8 days. In these tests the strength of specimens which were failed quickly was found to be about 25 per cent greater than the strength of specimens which were failed slowly.

Other investigators have performed tests on metals to determine their strength at various rates of strain. One comprehensive series of tension tests was performed by M.J. Manjoine 2) on a mild steel within the range of 1×10^{-6} to $1 \times 10^{+3}$ strain per second, which corresponds to a range of time to reach the ultimate strength of approximately 2.3 days to 0.0002 seconds. The ultimate strength of specimens tested in the shortest time was found to be about 1.5 times greater than that of specimens tested in the slowest time.

For tests on soils and soft rocks it was necessary to develop apparatus for applying dynamic loads and for measuring and recording the loads applied and the resulting deformations of test specimens.

APPARATUS FOR MEASURING AND RECORDING TRANSIENT LOADS AND DEFORMATIONS.

The type of loading desired is a transient load in which the test specimen is subjected to a rapid loading and unloading, simulating the effect of the first stress wave created by an explosion. The value for the fastest time of loading for use in this investigation was determined in consultation with Professors H.M. Westergaard x) and L.D. Leet xa) special consultants to The Panama Canal. The value thus decided upon was 1/100 second. The time for the slowest loading was determined by the desire to overlap with the fastest loading time used in static strength tests.

A comprehensive study was made of available intruments for measuring and recording transient compressive forces and deformations. In this study, advice was obtained from the David Taylor Model Basin, USN, Washington, D.C., and from Mr. A.C. Ruge xb).

Several months of intensive work were required to develop the load and deformation gages, check their functioning with the amplifying and recording equipment, and make the necessary adjustments and changes to produce satisfactory performance. A brief description of this instrumentation follows.

Load Gage. For measuring load, a load gage is used of rectangular or cylindrical shape, Fig. 1, with four SR-4 (metal electric) strain gages mounted on the inside face.

Deformation Gage. For measuring deformation, a thin flexible steel spring cantilever is used, Fig. 2, with SR-4 strain gages mounted on the cantilever, the base of which is clamped to the loading piston. The tip of the cantilever reacts against an adjustable screw which is mounted on the head plate of the triaxial compression apparatus.

Recording Apparatus. Equipment for amplifying and recording the signal produced by the SR-

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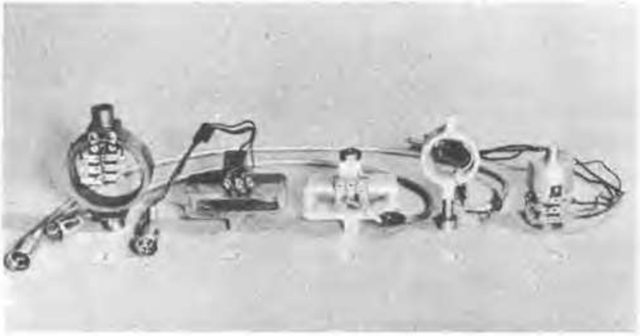
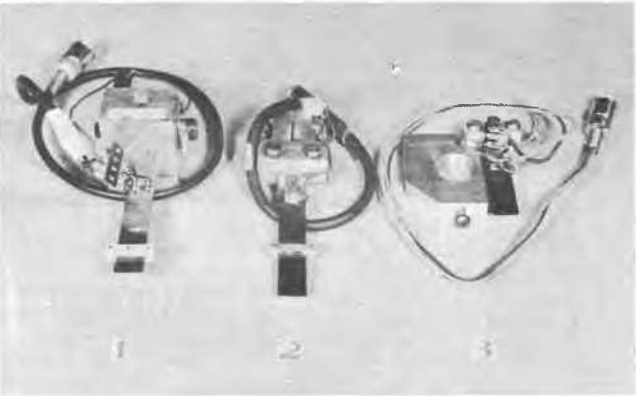


Load gages

FIG. 1



Deformation gages

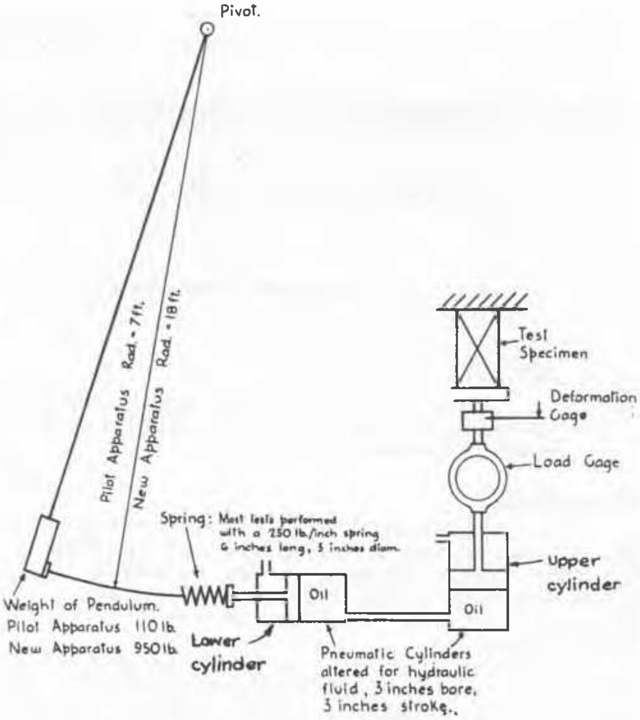
FIG. 2

4 strain gages consists of two strain indicators, a power supply, and two Brush direct writing oscillographs. The strain indicators contain two arms of a Wheatstone bridge and a carrier type amplifier. The other two arms of the Wheatstone bridge are the SR-4 strain gages on the load or deformation gages. With this equipment, loads and deformations applied to test specimens can be measured provided that the time of loading is greater than about one-sixtieth second, which is the limit of the Brush oscillograph. The Brush oscillograph has recently been replaced by a Hathaway oscillograph and companion strain indicators which will record transient loads and deformations with a time of loading as fast as 1/100 sec.

APPARATUS FOR APPLYING TRANSIENT LOADS

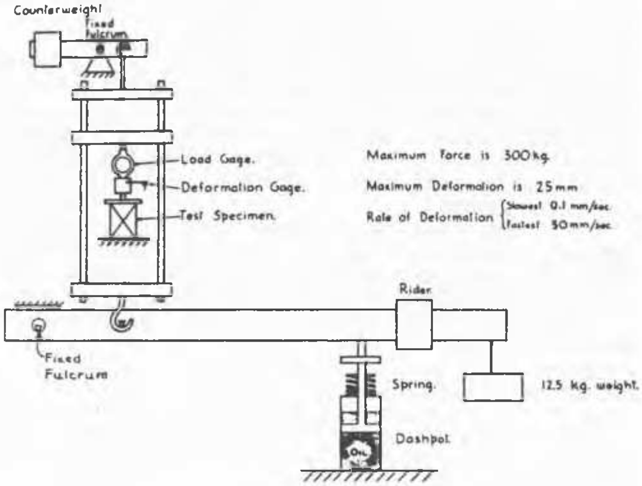
Three types of apparatus for applying transient loads in triaxial compression and unconfined compression test were simultaneously developed.

The Pendulum Apparatus utilizes the energy of a pendulum, as shown in **Fig. 3**. The pendulum is released from a selected height and strikes a spring which is connected to the piston rod of a 3 in. bore cylinder. This lower cylinder is in turn hydraulically connected to an upper cylinder of the same bore which is mounted within a loading frame. Fig. 3 shows the arrangement of the load gage and deformation gage for the performance of an unconfined compression test.



Pendulum apparatus

FIG. 3

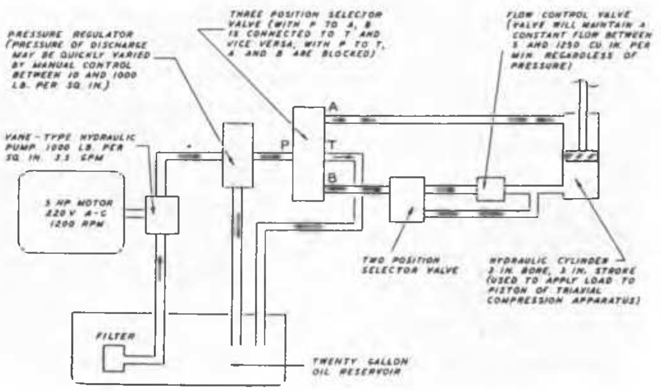


Falling beam apparatus

FIG. 4

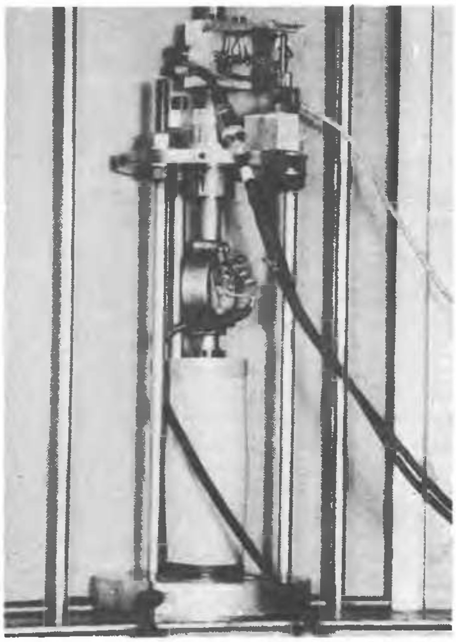
The Falling Beam Apparatus, illustrated in Fig. 4, utilizes the unconfined compression test apparatus of the "universal soil loading machine" 3) for the application of a transient load. The apparatus consists essentially of a beam with a weight and rider, a dashpot to control the velocity of the fall of the beam, and a yoke for transmitting the load from the beam to the specimen. A small beam mounted above the yoke counter-balances the weight of the beam. For the performance of an unconfined compression test the load gage and deformation gages are mounted as shown in Fig. 4.

The Hydraulic Apparatus, Fig. 5, consists of a constant volume vane-type hydraulic pump connected to a hydraulic cylinder through valves with which either the pressure in the cylinder or the volume of liquid delivered to



Hydraulic load apparatus

FIG. 5



Vacuum-type triaxial compression apparatus

FIG. 6

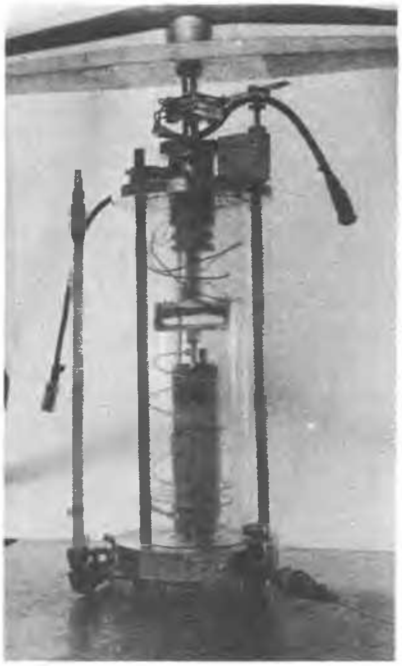
the cylinder can be controlled. The peak load which can be produced using this apparatus is much greater than can be obtained by either the falling beam or the pendulum types of apparatus. This apparatus will be used for testing various types of soft rocks from the Canal Zone.

APPARATUS FOR STATIC COMPRESSION TESTS

Two types of apparatus were used for determining the static compressive strength.

The Fairbanks Scale Loading Apparatus consists of a conventional 500 lb Fairbanks platform scale which is equipped with a loading yoke and a mechanical jack. It is used to perform tests with stress control.

The Hydrostatic Apparatus consists essentially of the two hydraulic cylinders of the pendulum apparatus and a motor-driven drum and lever with which the travel of both hydraulic pistons can be controlled at a constant, slow rate.



Compression-type triaxial compression apparatus

FIG. 7

TRIAXIAL TRANSIENT COMPRESSION APPARATUS

All triaxial compression apparatus used in this investigation for transient load tests have been adapted from triaxial apparatus previously constructed at the University for stat testing 4), 5). One of these is a vacuum type and three are compression types. The vacuum-type apparatus, Fig. 6, is limited to tests on non-cohesive soils under a minor principal stress less than one atmosphere. The compression-type apparatus, Figs. 7 and 8, is suitabl for tests on either cohesive or non-cohesive soils under a minor principal stress up to about 6 kg per sq cm.

MATERIALS TESTED AND TECHNIQUE OF TESTING

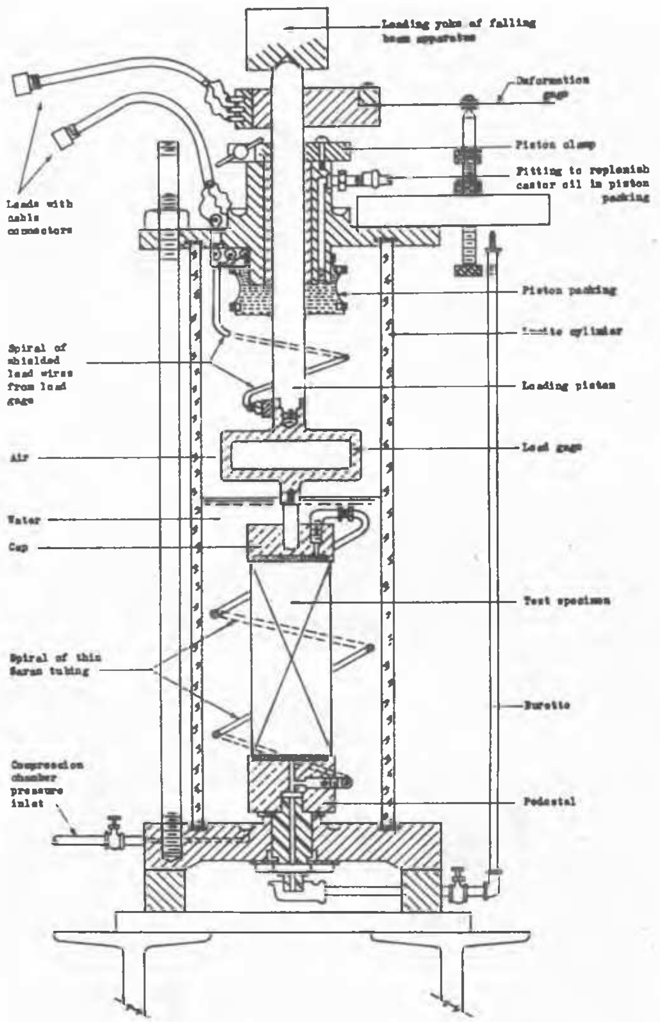
Static and transient compression tests have been performed on the following materials

Manchester (N. H.) Sand is a clean, medium sand obtained by screening from a glacial-fluvial deposit and contains only the fraction between 0.42 mm and 0.21 mm. It consists principally of subangular quartz grains, and has a void ratio in the dentest state of about 0.6 and in the loosest state of about 0.88.

The Manchester sand was compacted to a dense state in a vacuum type triaxial compression apparatus and tested dry. Each test specimen was 7.1 cm in diameter and about 18 cm high.

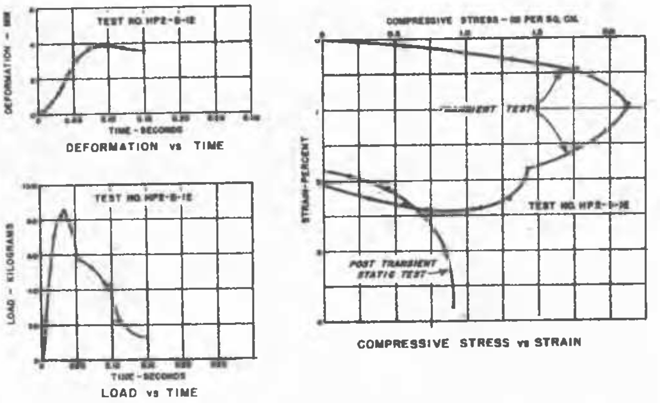
Cambridge (Mass.) Clay is a medium soft clay, with occasional thin silt partings, brittle in the undisturbed state and soft and stick when remolded. Its natural water content ranges from 30 to 50%. For layers of this clay having a natural water content of 40 to 50%, the liquid limit was found to range from 44 to 59 and the plastic limit from 21 to 27. For layers of this clay having a low natural water content (30 to 40%), the liquid limit was foun to range from 37 to 44 and the plastic limit from 20 to 23.

Boston (Mass.) Clay is similar, geologic-



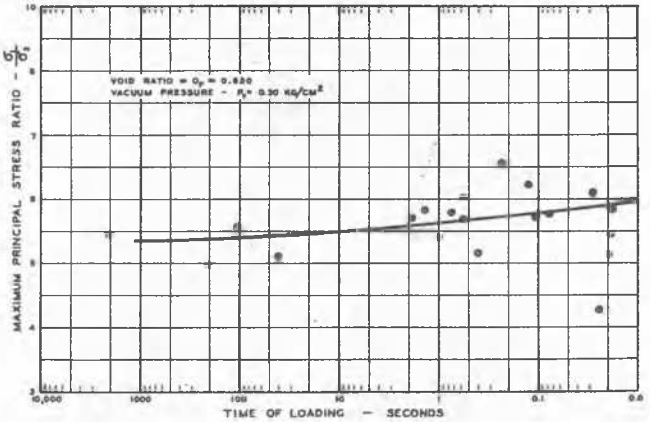
Compression-type triaxial transient compression apparatus

FIG. 8



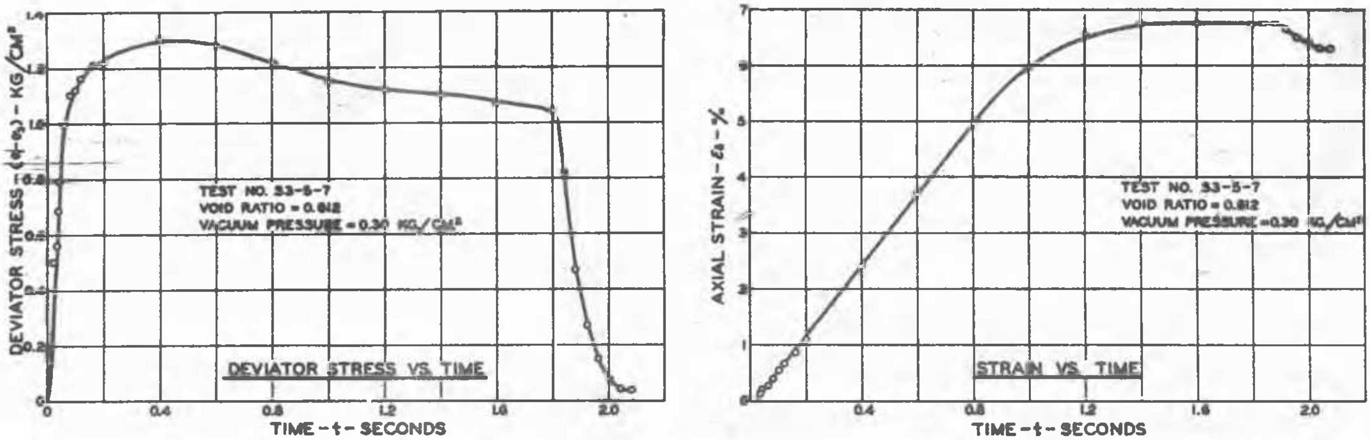
Typical transient unconfined compression test on Cambridge clay

FIG. 9



Results of tests on sand

FIG. 11



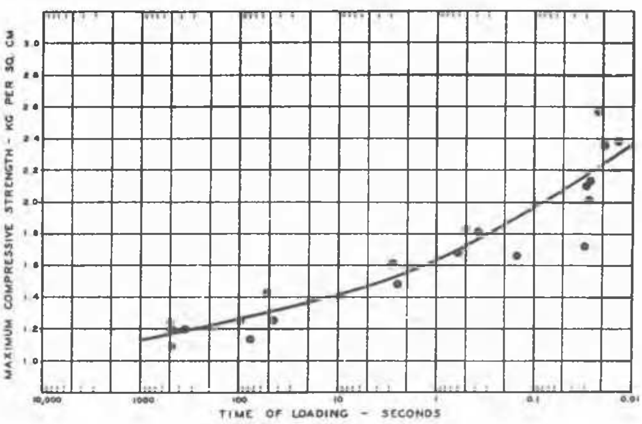
Typical triaxial transient compression test on Manchester sand

FIG. 10

ally and in its appearance, to the Cambridge Clay. The Boston clay tested had a natural water content between 32 and 36 per cent, a liquid limit averaging 42 and a plastic limit of 20.

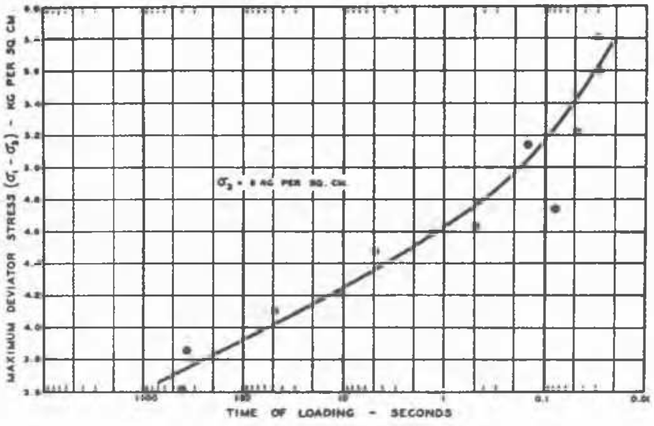
<u>Stockton (Calif.) Clay</u> is a tough brown clay, almost fully saturated, having a natural water content of about 25 per cent, a liquid limit of 60 to 64, and a plastic limit of 20 to 23. The sample tested was obtained from a compacted fill. A compaction plane was found in the middle of the sample.

The Cambridge and Boston clays were tested



Results of unconfined compression tests on soft clay

FIG.12



Results of triaxial compression tests on soft clay

FIG.13

both in unconfined compression and in triaxial compression, whereas the Stockton clay was tested in triaxial compression only.

Unconfined compression test specimens were 6.3 cm square and about 16 cm high; triaxial compression test specimens were 3.56 cm in diameter and about 9 cm high.

The triaxial compression test specimens were surrounded by a rubber membrane averaging 0.05 mm in thickness and were fulle consolidated under a lateral pressure of 6 kg/cm^2 before axial compression was started.

Two types of triaxial compression tests were performed, designated "quick" and "consolidated-quick". A quick triaxial compression test is one in which there is no preliminary consolidation and no drainage of pore water during the test. A consolidated-quick triaxial compression test is a test in which the specimen is allowed to consolidate under a hydrostatic pressure, but during the subsequent quick axial loading there is practically no drainage of pompwater.

Two procedures for performing transient compression tests were used, which are described below:

Controlled Impulse Method. The specimen is subjected to a controlled impulse. The peak load exerted on the test specimen and its deformation depend on the stress-deformation and strength characteristics of the specimen. Typical load-time and deformation-time diagrams for an unconfined transient compression test on clay, using the controlled impulse method, are shown in Fig. 9.

Controlled Strain Method. The specimen is subjected to a rate of strain which is maintained approximately constant from the start of the test to the desired maximum strain. The peak load exerted on the specimen and the time of loading depend on the stress-deformation and strength characteristics of the specimen. Typical deformation-time and load-time diagrams for a test on sand, using the controlled strain method, are shown in Fig. 10.

RESULTS OF TESTS

Representative test results for an unconfined compression test on Cambridge clay and a triaxial compression test on Manchester sand are shown in Figs. 9 and 10. From a number of such tests, the relation between compressive strength and time of loading is determined, as shown by the typical plots, Figs. 11, 12 and 13. Time of loading is defined as the difference in time between the start of test and the time at which the maximum compressive stress is reached. Fig. 14 is a summary sheet showing the generalized relationships between compressive strength and time of loading as obtained from all the tests performed on clay to the time of writing.

The original purpose of the investigation did not include the determination of the stress-deformation characteristics. Therefore, precise measurements of the deformation at small loads in transient tests have not yet been made. However, the tests performed on Cambridge clay have been analyzed as well as possible for the purpose of arriving also at some information regarding the effect of time of loading on the initial slope of the stress-deformation curve as represented by the modulus of deformation. For the purpose of this investigation, the modulus of deformation is defined as the slope of a line drawn from the origin through the point on the stress-deformation curve corresponding to a stress of one-half the strength.

The order of magnitude of the modulus of deformation, as obtained from the tests performed on clay samples, is summarized in the following Table I :

TABLE I

Modulus of Deformation

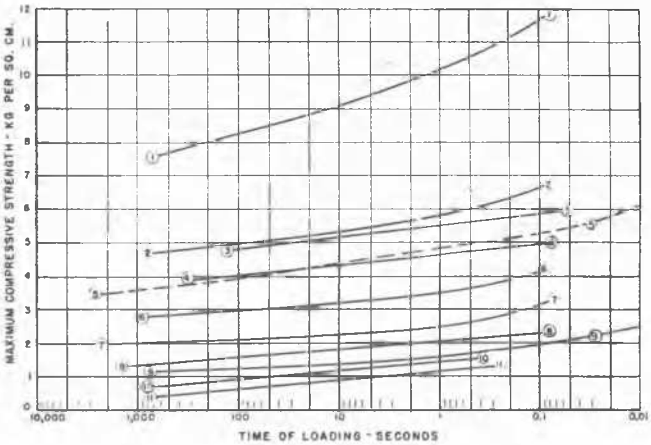
Material	Type of test	Order of Magnitude of Modulus of Deformation kg/cm^2	
		Static Tests	Transient Tests
Boston clay	Quick Triaxial σ_3= 6 kg/cm^2	250	500
Stockton clay	Quick Triaxial σ_3= 6 kg/cm^2	250	500
Cambridge clay	Consolidated-quick Triaxial σ_3=6 kg/cm^2	650	1300

CONCLUSIONS

The following conclusions are tentatively drawn from the tests performed on the samples of clay and sand.

LEGEND FOR FIG. 14.

Curve No.	Sample No.	Material	Type of Test	Water Content at time of Test %
1	HP-6-C	Cambridge clay which was slowly dried to slightly higher than its shrinkage limit	Unconfined compression	27
2	HP-6-C	Cambridge clay which was slowly dried to a water content of about 14% less than its natural water content	Unconfined compression	33
3	HP-6-B	Cambridge clay	Consolidated-quick triaxial compression $\sigma_3 = 6$ kg/cm^2	24 to 32
4	HP-6-A	Cambridge clay	Consolidated-quick triaxial compression $\sigma_3 = 6$ kg/cm^2	32 to 35
5	HP-6-D	Cambridge clay	Consolidated-quick triaxial compression $\sigma_3 = 6$ kg/cm^2	40 to 44
6	HP-6-C	Cambridge clay which was slowly dried to a water content of about 10% less than its natural water content	Unconfined compression	37
7	HP-7-A	Stockton clay	Quick triaxial compression $\sigma_3 = 3$ kg/cm^2	24 to 27
8	HP-5-A	Boston clay	Quick triaxial compression $\sigma_3 = 3$ kg/cm^2	32 to 35
9	HP-2	Cambridge clay	Unconfined compression	34 to 39
10	HP-6-B	Cambridge clay	Unconfined compression	35 to 40
11	HP-6-A	Cambridge clay	Unconfined compression	40 to 42



Compressive strength vs time of loading for all test series on clay

FIG.14

1) The strength of clay increases with decreasing time of loading, the transient strength for the fastest tests in this investigation being from 1.5 to 2 times the static strength. The percentage increase in strength is dependent on the static strength. Samples with a low static strength had a greater percentage increase than those with a high static strength. The increase in strength due to time of loading is independent of the method of testing.

2) The strength of sand increases only slightly with decreasing time of loading. The maximum increase for the fastest tests in this investigation was about 10%

3) The modulus of deformation of clay for the tested transient tests in this investigation was about twice that for static tests.

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