Load-Time Relationships In Direct Shear of Soil

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Development of a direct shear apparatus capable of failing a soil specimen in a time interval ranging from a few milliseconds to days is described. The apparatus, referred to as DACHSHUND I, utilizes a pneumatic system for the application of both static and dynamic loads. Special design features include impact accelerators and a double triggering system that allows either separate or synchronous application of normal and shear loads. The maximum shear and normal load capability of the pneumatic system is 500 lb. Soil specimens up to 4 in. in diameter and 0.75 in. thick can be accommodated by the shear box.

Preliminary static and dynamic test results conducted on Standard Ottawa Sand and Jordan Buff Clay indicate that the shear strength of dry sand is insensitive to loading rate, whereas the strength of an unsaturated clay increases with increased loading rates.

•THE WORK described in this paper is part of a broad research effort sponsored by the United States Air Force with the ultimate objective of obtaining dynamic shearing and frictional force data on soils for use in the design of protective structures and in the interpretation of laboratory experiments in soil dynamics. The objective of this part of the research effort is to design and build a direct shear-type device with which soils of all types can be forced to fail on a chosen plane by either dynamic or static loadings. In addition, the device should be capable of recording the time history of normal and shearing loads and deformations reasonably close to those on the failure plane. Such a device could be very useful in the highway field, as well as in military construction.

DESIGN CRITERIA

An exhaustive literature search resulting in a sizable annotated bibliography by Woods (6) did not reveal any previous investigations of the dynamic strength of soil using direct shear devices. However, the soil characteristics determined by other methods can be used as guides for choosing the design criteria for a direct shear device. In the following discussion, the static and dynamic soil characteristics found by other investigators are considered in the development of the design criteria.

Specimen Size

The grain size of the soil to be tested determines the minimum size of test specimen because of the need to develop a macroscopic effect across the shear plane. Too thick a specimen may induce progressive shear failure, whereas too thin a specimen may

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not be able to accommodate the larger grain sizes. For soil with grain sizes up to fine gravel, a compromise thickness of 0.75 in. and a diameter of 4 in. was chosen.

Shear Deformation Capacity

Previous investigators have found that shear failure occurs in soils at a wide range of deformation values. Stiff shale-like clay was reported by Casagrande and Shannon (2) to reach peak load at about 1 percent strain in triaxial compression tests. The same authors found that a disturbed soft muck, in an unconfined compression test, did not reach peak load before 30 percent strain. Other authors report values between these for various soils. Use of the method suggested by Taylor (4) for calculating the shear strains in compression and direct shear indicates that the direct shear deformation corresponding to Casagrande and Shannon's 30 percent compressive strain would be more than 0.5 in. for a soil specimen 4 in. in diameter and 0.75 in. thick. Thus, in order to accommodate ultimate strains that may be in excess of peak strains, it was decided that the device should be capable of applying maximum shear deformations of 1.25 in.

Load Capacity

An absolute value for the maximum normal and shear force that the device should be capable of applying to the soil specimen is not easily chosen. The wide range in the shearing resistance of soil and the time dependency of the shear strength of a particular soil sample makes it difficult to assign a maximum value. In sands the shearing strength is controlled by the normal pressure on the shearing plane, and the required shearing force should not exceed the normal force. On the other hand, there is no such direct relation for cohesive soil. Whitman (5) has measured dynamic compressive strengths as high as 400 psi for a stiff clay soil. Thus, the shear strength would be 200 psi if the shear strength is one half the compressive strength. A 4-in. diameter sample could be made to fail with a shear force of 2,500 lb. However, by adding filler rings in the shear box, a soil sample 1 in. in diameter could be failed using a force of only 160 lb. With this sort of data in mind, as well as the static strengths of average soils, it was decided that the apparatus should be designed to apply a maximum force of 500 lb normal and parallel to the shear plane. Especially strong soils could then be tested by using filler rings and smaller diameter samples.

Minimum Loading Time

Whitman (5) and Richardson (3) have attempted to obtain minimum loading times of 1 msec; but in doing so with the cylindrical compressive specimens they encountered wave propagation and lateral inertial problems that limited the meaningful rise time to a value of about 10 msec. This type of restriction is less evident in a direct shear test and, therefore, it seemed feasible to attempt to develop a device that could apply the failure load in about 1 msec.

METHOD OF LOAD APPLICATION

Literature review revealed that previous investigators had used testing devices that fell into five general categories as to their manner of load application. Each of these categories was reviewed and considered for the project.

Gravity Testers

Three types of gravity testers have been used. One type simply drops a weight from a preselected height in a guide rail system. Another type accelerated the falling weights by means of elastic cords. The last type, the pendulum, allowed a suspended weight to be raised to a preselected height and released to strike the specimen at maximum velocity. All gravity testers accomplished the rapid loading desired and were simple to operate, but they lacked flexibility and were very bulky.

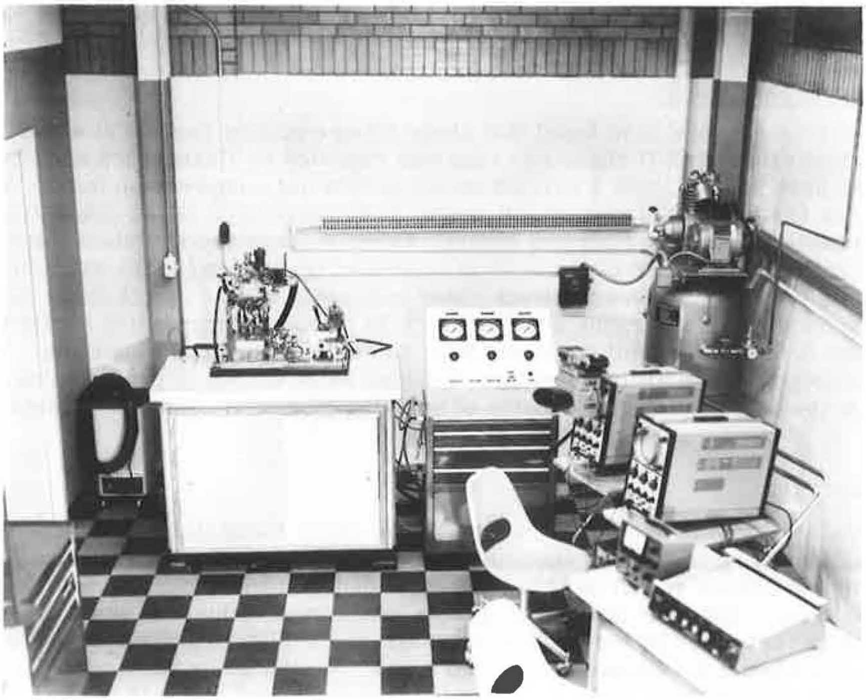

Figure 1. Laboratory facility.

Explosive-Operated Testers

The entire category of explosive-operated devices was discarded from consideration for this project because of their inflexibility and hazardous nature.

Shock Tubes

Whereas shock tubes were suggested as a possible loading type in the early work on the project, further consideration showed that such an apparatus could not be made compact enough for ordinary use and would be difficult to operate in the static range.

Hydraulic Loading Machines

Hydraulic loading machines can be used for all loading speeds desired and meet all other criteria established for the apparatus design. However, the valving and pumping equipment are more complex than for a pneumatic system.

Pneumatic Loading Machines

Pneumatic loading machines also meet all criteria established for the design of the apparatus and seem to offer the possibility of the most compact design.

After considering each of the over-all categories of loading arrangements, it was decided that the apparatus be a pneumatic loading arrangement designed around a standard configuration for the shear box. The developed apparatus has been given the name DACHSHUND I (Dynamically Applied Controlled Horizontal SHear—University of Notre Dame I). A photograph of the complete installation is shown in Figure 1 and a schematic representation of the various parts in Figure 2.

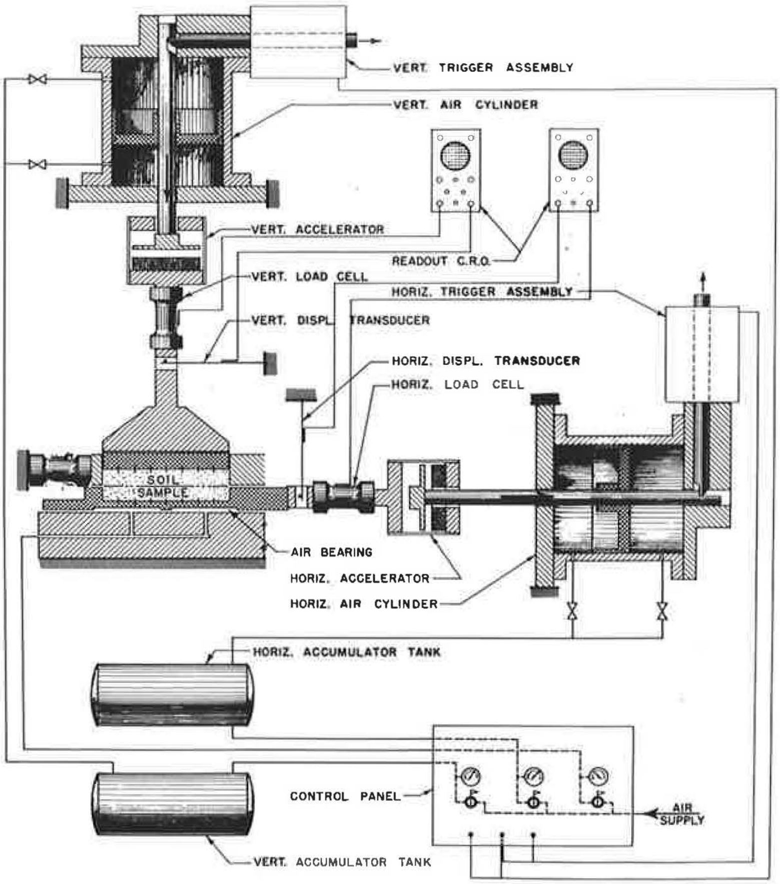

Figure 2. Schematic of apparatus—DACHSHUND I.

APPARATUS

Pneumatic System

The pneumatic system devised for applying loads to the soil sample consists of the following components: air compressor, two accumulator tanks, a vacuum pump, and two air cylinders. These components are supplemented by the necessary valving, piping, pressure regulators, and gages required to transmit and control the air as needed.

When a dynamic test is made, air is fed to the accumulator tanks from the air compressor through the pressure regulators. After the air pressure in the accumulator tanks has reached a predetermined value, the cylinders are locked in position by their triggering devices and air from the tanks is let into the rear of the cylinders and into the air bearing. The shear test is started by actuating the solenoids that cause the triggering device to release the pistons. The pistons are made to move rapidly by the expanding air and the soil is sheared off in a few milliseconds. The air pressure behind the moving piston is quickly reduced as the specially contoured skirts of the piston first cover the air inlet port and then uncover the outlet port in each cylinder. The air pressure is thus dissipated and the piston stops. Compression of air on the forward side of the piston can be used to help stop the piston, or a vacuum can be created to speed the forward motion. In either case, a rubber bumper at the end of the cylinder stops the piston at the end of its travel. The air gap in the vertical and horizontal accelerator is used to synchronize the application of normal and shearing loads or permit the pistons to gain speed before load application.

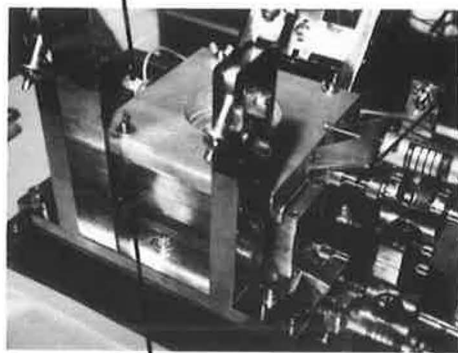

Figure 3. Shear box assembly.

When a slow shear test is to be made, the pistons are not locked in position and their motion is controlled by gradually increasing the air pressure in the accumulator tanks, cylinder and air bearing as desired to run a test in a predetermined time.

Shear Box

In a direct shear device, shearing action takes place between a fixed and a movable shear box. Because a high shear rate is sought, the lower shear box (Fig. 3) should be the movable member. This box is made of No. 43 casting aluminum, selected because of its high strength-weight ratio and its resistance to the corrosive action of moist soils. The moving shear box rests on a cushion of air provided by an air bearing, thus minimizing frictional resistance. Eccentric loads are resisted by four small ball bearings mounted in cages, recessed into the brass support plate at a depth allowing approximately a 0.002-in. clearance between the shear box and the plate under load. Four hardened stainless steel strips are inlayed into the bottom surface of the shear box for contact with the ball bearings.

Although the movable shear box slides on a relatively frictionless interface, significant inertial forces may distort the measured value of soil resistance. Therefore, the fixed or upper shear box was supported vertically by mounting it on four thin flexible columns and was restrained in a horizontal direction by fastening it to a load cell. Thus, shear loads can be measured on both the upper and lower shear boxes to evaluate inertial and friction forces and the shearing force on the soil.

Load Measuring Devices

Measurement of the normal and shearing forces applied to the soil sample involves two measuring systems. These are:

1. Bourdon Tube Pressure Gages. —For static load measurements, visual readout of Bourdon Tube pressure gages is made by the operator to ascertain the pressures corresponding to the normal and shearing forces being applied to the test sample, as well as the air bearing. Fine adjustments in these applied pressures may be obtained by manual adjustments of needle valve controlled pressure regulators. However, the pressures recorded on the gages include piston friction, which is not a constant.

2. Electronic Load Transducers. --Because the pressure gage readings are not a true measure of the force on the soil, an electronic load transducer near the soil is used for both static and dynamic tests. The load cell designed for the measurement of the normal and shearing forces applied to the test specimen (Fig. 3) consists of a thin-

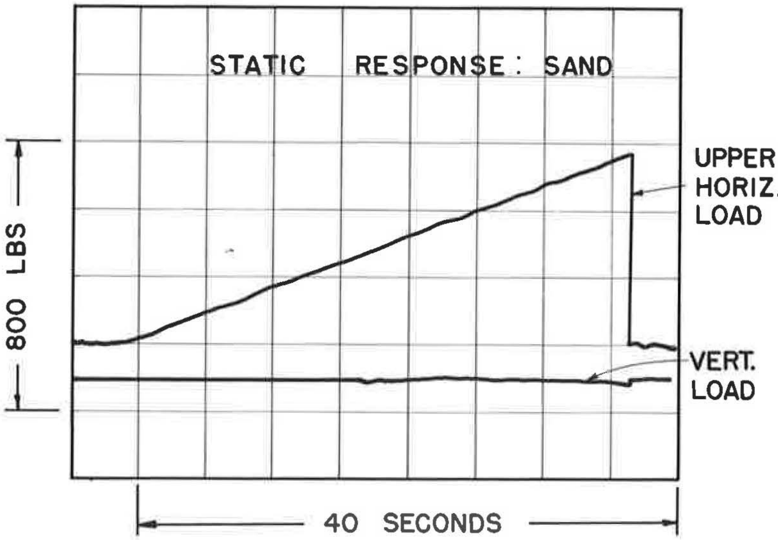

Figure 4. Static response: sand.

walled spool-shaped cylinder provided with enlarged threaded ends for the in-line connection to the piston rods. The transducing elements of the load cells consist of four wire resistance strain gages, cemented to the walls of the hollow cylindrical spool and connected to form a Wheatstone bridge circuit. The specific type of wire resistance strain gages used was SR-4, type CD-7. The output of the load cells is displayed on an oscilloscope and recorded with a camera during dynamic tests or on an X-Y recorder during static tests.

Displacement Measuring Devices

Both vertical and horizontal motions are measured just outside the shear box by linear varying potentiometers. For dynamic shear tests the output is shown on an oscilloscope and recorded with a camera, whereas for slow shear tests the output is recorded on an X-Y recorder.

EXPERIMENTAL RESULTS

A series of preliminary tests has been conducted on both a cohesionless and cohesive soil. The cohesionless soil is a Standard Ottawa Sand (20 to 30 sieves). Two relative densities have been studied. The cohesive soil is a Jordan Buff Clay sold commercially by the United Clay Mines, Trenton, N. J. The characteristics of this clay are: liquid limit, 54 %; plastic limit, 26 %; shrinkage limit, 22 %; plasticity index, 28 %; and specific gravity, 2.74. The clay was purchased in powder form, mixed with distilled water to a moisture content of approximately 31 % and compacted to a wet density of 114pcf.

To compare the behavior of DACHSHUND I with conventional direct shear machines, a series of static calibration tests was run. Figures 4 and 5 indicate a typical set of results on the Ottawa Sand for a test duration of approximately 40 sec. The shear load was increased manually at approximately a linear rate.

The failure envelopes obtained from a series of such static tests on the Ottawa Sand in both loose and dense conditions are shown in Figure 6. The resulting friction angles are compared with those previously reported by Burmister (1) (Table 1).

Despite the unique features of DACHSHUND I, it is capable of imposing essentially the same force system on a soil specimen as the more conventional direct shear devices.

Figures 7 and 8 show a typical set of traces recording the dynamic response on the same Ottawa Sand. Pressure was developed in the horizontal cylinder while the piston was restrained by the triggering system. On release of the trigger, a shear load was

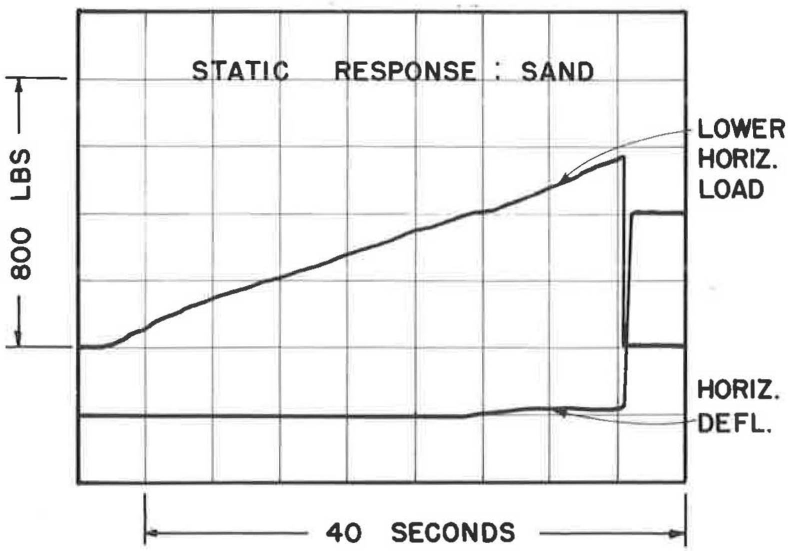

Figure 5. Static response: sand.

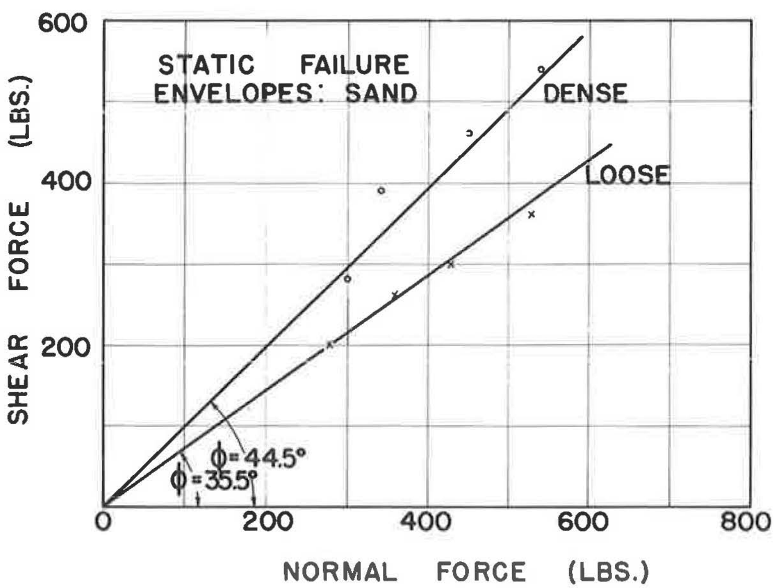

Figure 6. Static failure envelopes: sand.

TABLE 1

STATIC TEST RESULTS AT VARYING DENSITIES

Soil	Rel. Density	Friction Angles, ϕ (deg) DACHSHUND I	Friction Angles, ϕ (deg) BURMISTER
Ottawa Sand	90%	44.5	43
Ottawa Sand	33%	35.5	37

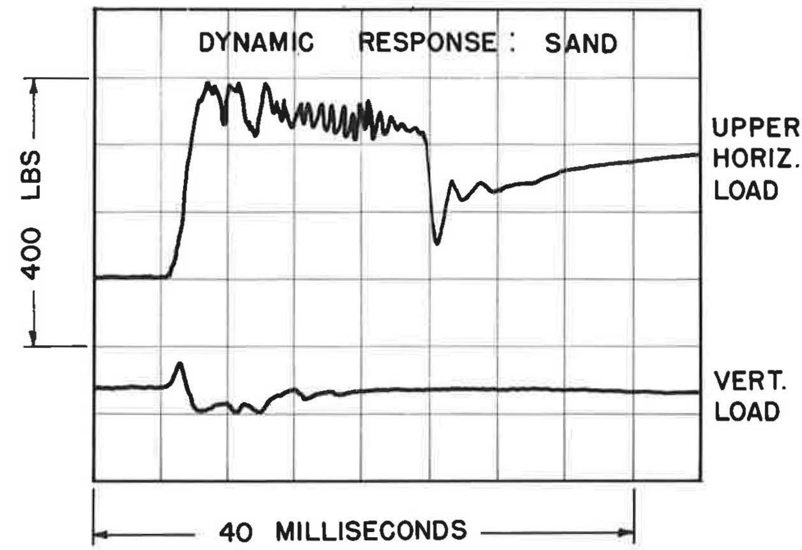

Figure 7. Dynamic response: sand.

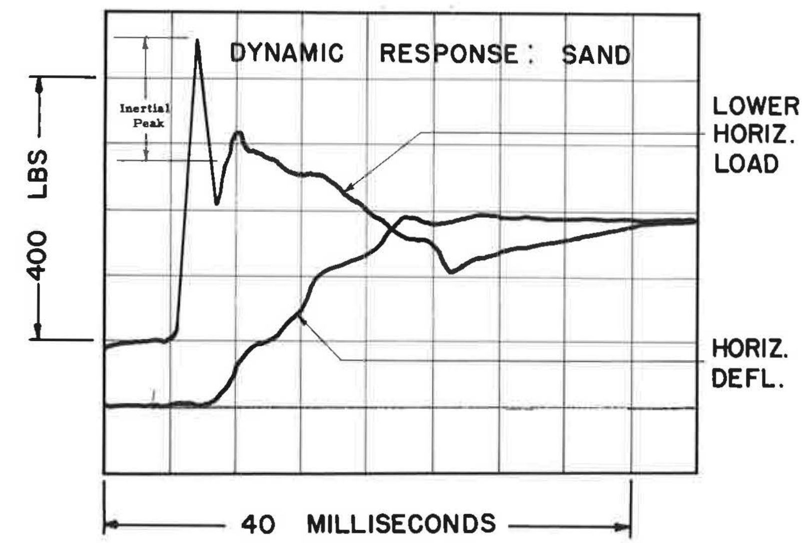

Figure 8. Dynamic response: sand.

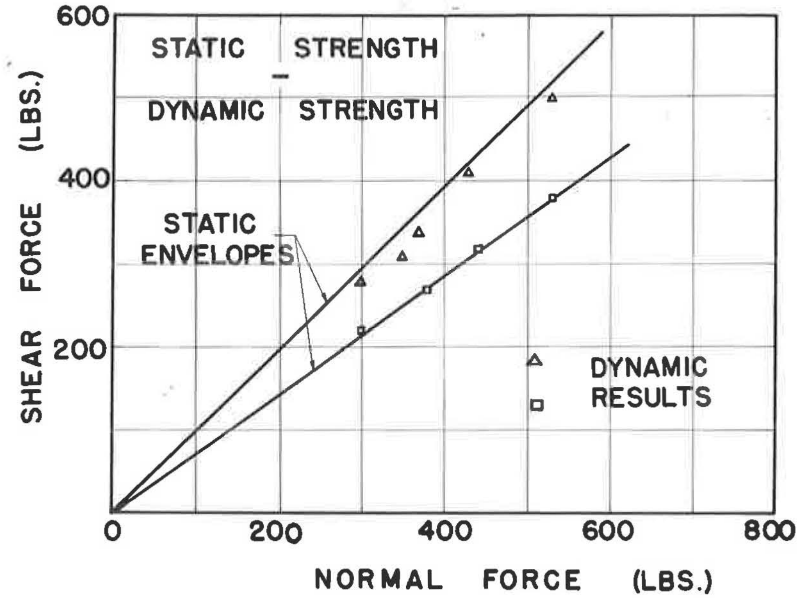

Figure 9. Comparison of dynamic strength and static envelopes: sand.

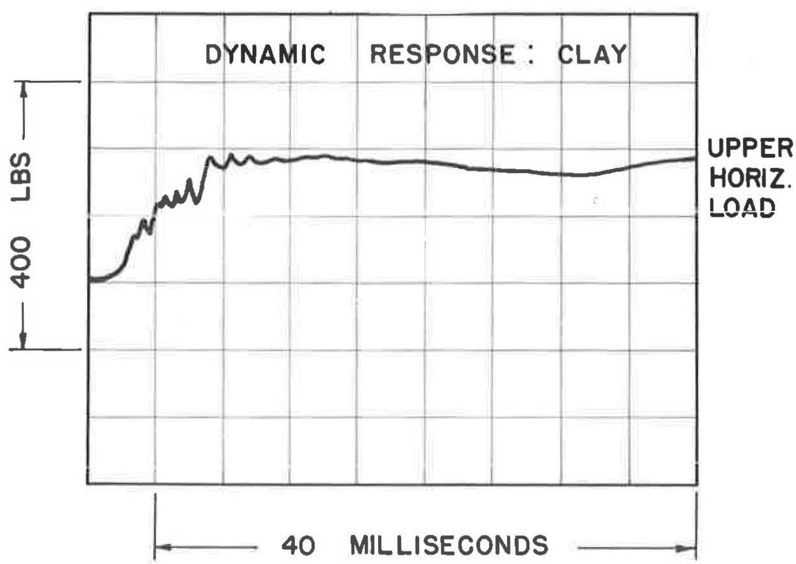

Figure 10. Dynamic response: clay.

imposed on the specimen resulting in a time to failure of approximately 3 msec. From the direction of the forces involved, it was concluded that the peak in the lower horizontal load cell trace was due to the acceleration of the lower tray. Based on this conclusion and by varying the mass of the lower tray, the inertial force as shown was determined. The remaining force, equal to the total force minus the inertial peak, was applied to the specimen as dictated by the agreement between the "action" and "reaction" load cells.

Figure 9 compares the results of the dynamic sand tests, all of which involved times

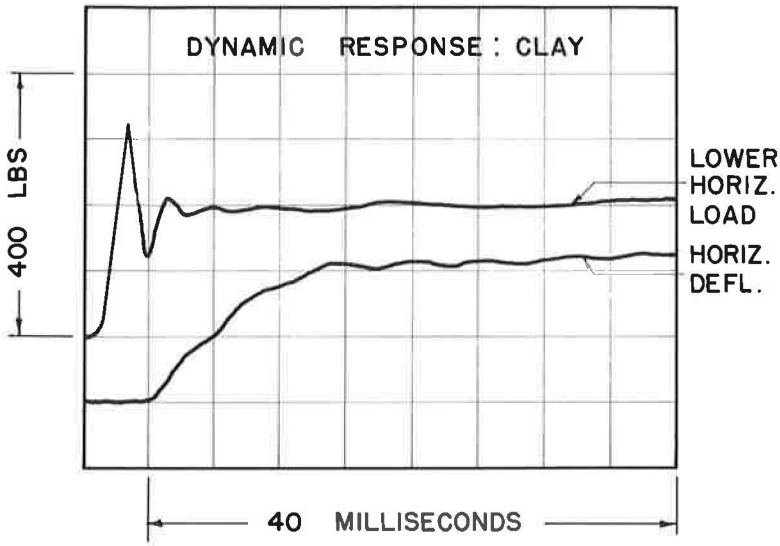

Figure 11. Dynamic response: clay.

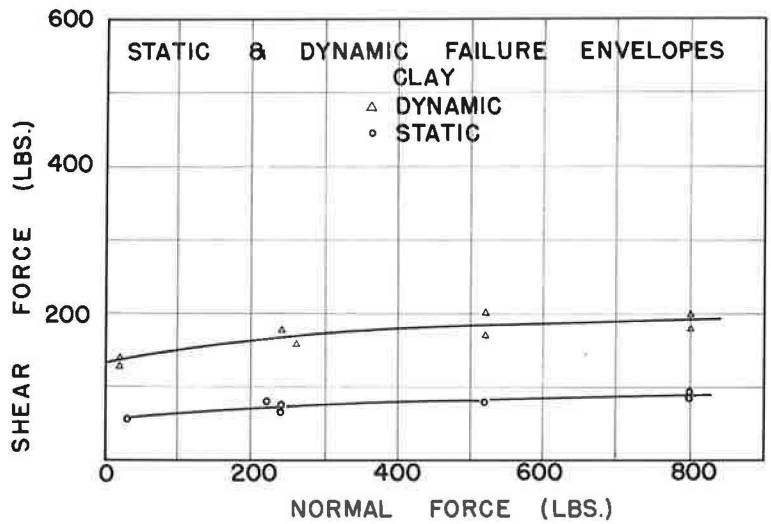

Figure 12. Static and dynamic failure envelopes: clay.

to failure between 0 and 5 msec, and the static failure envelopes. This plot clearly indicates that the strength of the dry Ottawa Sand tested is insensitive to load rate effects, thus verifying the results obtained by Whitman (5) in triaxial compression.

The next phase of the investigation involved essentially a repetition on the Jordan Buff Clay of the previously described static and dynamic test. The static test traces were similar to those in Figures 4 and 5; however, the dynamic trace characteristics differed somewhat from those reported on the sand. Figures 10 and 11 are a typical set of dynamic test results for the compacted clay.

The static and dynamic strength envelopes for the Jordan Buff Clay are shown in Figure 12. The dynamic envelope is comprised of tests with time to failure in the 0 to 5 msec range, whereas the static envelope involved test durations of approximately

0 to 40 sec. An examination of Figure 12 indicates that at any particular value of the normal load, the dynamic shear strength is approximately twice the static value. These results certainly demonstrate the time dependent strength characteristics of the unsaturated clay under consideration; however, the wide spread in test duration should be remembered.

An additional comparison between static and dynamic response is the load deflection characteristics of the soils tested (Fig. 13).

For the compacted clay, the increase in strength associated with the dynamic tests appears to be accompanied by an increase in deflection or strain at peak load. The dry Ottawa Sand, which displayed no strength variations as a function of load rate, reached peak load at a very small deflection in both the static and dynamic cases. These conclusions regarding the load deflection response should be treated as tentative due to the degree of interpretation required in "matching" the individual load and deflection traces.

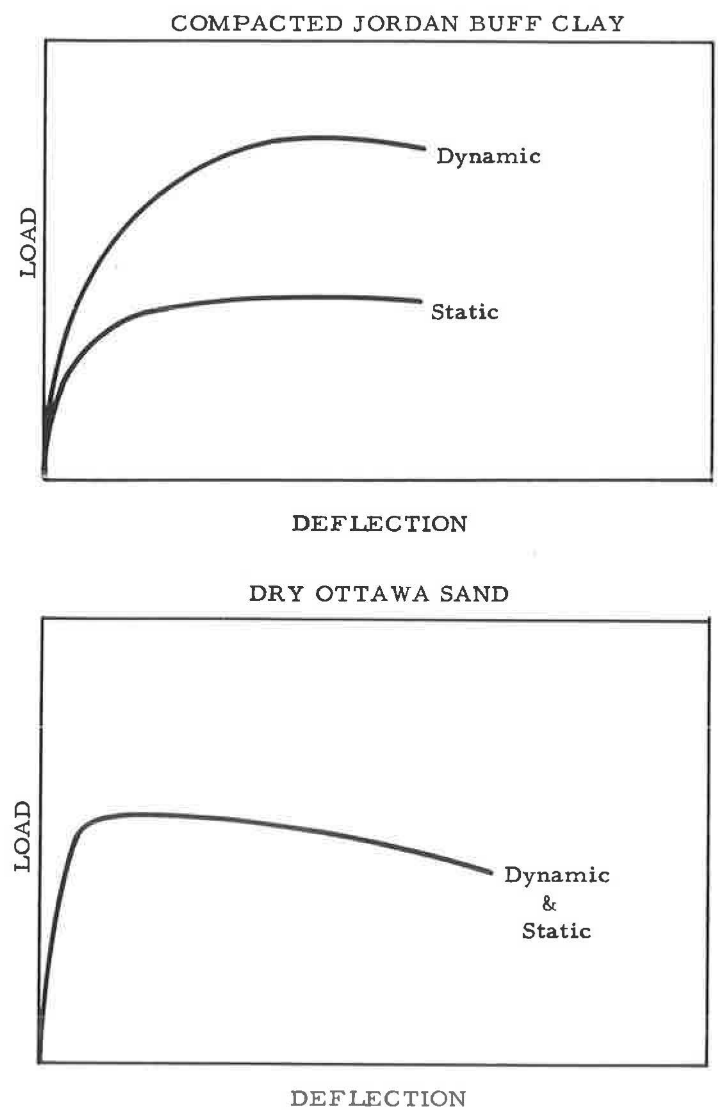

Figure 13. Load displacement relations.

CONCLUSIONS

A direct shear-type device has been developed that is capable of imposing shear loads on a soil specimen over a wide range of loading rates. In the conventional time range, it duplicates the behavior of standard-type direct shear machines.

Preliminary dynamic results appear to corroborate, at least in a qualitative sense, the findings obtained from dynamic triaxial compression tests.

The two-dimensional dynamic capabilities of the apparatus offer the promise of greater insight into the dynamic behavior of soils.

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