Experiments on Vibratory Cutting of Soils

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This article reports a series of small-scale, laboratory investigations comparing the effects of cutting soil and soil-like materials by a combination static-plus-oscillatory loading with the effects of cutting by a purely static load. The cutting apparatus consists essentially of a blade and cutting head to which is attached a variable speed motor that rotates a small unbalanced weight at frequencies up to about 100 cycles per second. Three types of materials were investigated, including a sand, a silty clay, and an artificial material (Plasticene) resembling a clay in some of its properties. The moisture contents of the sand and of the clay were varied; however, the tests on the sand were generally conducted at optimum moisture content and the tests on the clay at the plastic limit. Temperature was found to be an important factor in the tests using Plasticene. The materials were compacted in rigid molds by the use of a Proctor hammer. Three types of support of the cutting head were investigated, one having a single degree of freedom, one 3, and one 6 (restrained only by a very "soft" spring suspension). The tests were compared on the bases of cutting displacement and time. In general, it was found that the use of the oscillatory loading was advantageous, the advantage residing primarily in the considerable reduction of the static component of the load (reduction in weight of cutting head, i. e., in static force required to push the cutting blade).

● THIS report is on a preliminary series of comparative laboratory experiments in the cutting of soils and soil-like materials by a blade loaded statically and dynamically. The dynamic load was generated by an unbalanced centrifugal force rotating at frequencies well below any apparent resonance. The purpose was to explore the possible advantages of dynamic-plus-static, versus purely static loading, with a view to the application of dynamic loading in earth moving and excavation equipment, tube driving, etc.

Within the limitations of the laboratory, the use of dynamic loading shows a considerable advantage in decreased weight of equipment and, by implication, in decreased "drawbar" force. However, in order to evaluate the overall advantage in application to full-scale equipment, it would be necessary to make a complete economic study involving equipment design, initial and operating costs, and field tests. The results appear to be sufficiently promising to warrant further investigation, particularly of various methods of generating the dynamic loads, of larger scale systems, of resonance, and of a more complete range of soil conditions. Further tests are planned.

Several questions had to be answered during the course of the investigation. They include the choice of a unit of cutting-measurement (time, as well as displacement, is an important variable), a criterion of comparison between the static tests and the dynamic tests, the types and conditions of "soil," the loading and cutting apparatus, and the frequency range of the dynamic load component.

Considerable work has been done over a period of many years on the vibratory compaction of soils (*1*, *2*). However, the author is not aware of a prior investigation directed specifically to the cutting of soils by vibratory methods. A paper appeared recently on a related subject, the driving of piles by vibration (*3*).

LABORATORY APPARATUS

Three types of cutting apparatus were developed for investigation. In each one the blade is attached to a cutting head to which is attached a variable speed motor that rotates a small unbalanced weight at frequencies up to about 100 cycles per second. The differences among the apparatus types are mainly in the manner of guiding and restraining the cutting head and in the direction of cutting the "soil" sample. In two of the types, the blade penetrates into the soil from the surface in the manner of a spade. In the first of these, the cutting head is restrained so that it can move only in the direction of blade penetration (1 degree of freedom). In the second, the head is suspended elastically by springs so that it has maximum freedom of motion (6 degrees of freedom). In the third type, the motion of the cutting head is limited to 3 degrees of freedom in the plane of the blade, and the blade is inserted into the soil and then pulled by a force parallel to the surface of the soil. This results in a continuous, constant depth, slicing of the soil.

In the penetration apparatus the cutting blade is a 0.050-inch-thick flat brass plate, 1.67 inches long (vertically), and 3.25 inches wide (length of cutting edge), with the edges filed to a V-shape in cross-section. The blade is the same in the slicing test apparatus, except that the cutting edge is vertical and is 1.00 inch long and the horizontal length is 3.00 inches.

Rigid cylindrical containers, similar to Proctor molds, were used in the penetration tests. Long, rigid, trough-like containers were employed in the slicing tests. Compaction was accomplished by means of a standard Proctor hammer. The soil was tamped in the cylindrical containers in three layers of about equal thickness, each layer in turn being subjected to 25 blows by a 5.5 pound hammer, 2.0 inches in diameter at the striking surface, each blow having a free fall of 12 inches. The tamping in the trough-like containers was carried out in a similar manner.

The speed of the motor was adjusted by use of a variable transformer and determined by a stroboscopic tachometer.

In the case of the penetration tests, the depth of blade penetration was recorded continuously against time on a constant-speed mechanical drum recorder. In the slicing tests a stop-watch was used to record the time of travel of the blade through a specified distance. Each test was repeated at least once.

The manner of starting a penetration test is

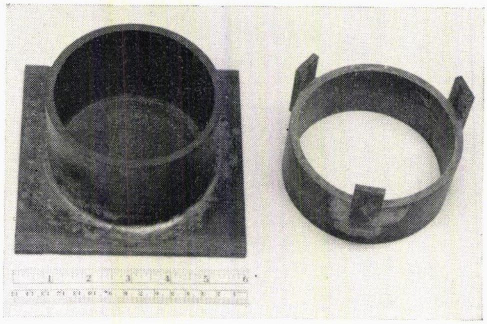

Figure 1. Soil-sample container for penetration tests. Inside dimensions: diameter = 4.00 inches; depth = 3.00 inches.

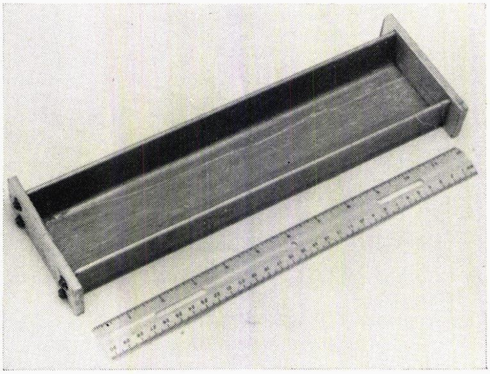

Figure 2. Soil-sample container for slicing tests. Inside dimensions: 2.50 by 1.25 by 12.00 inches.

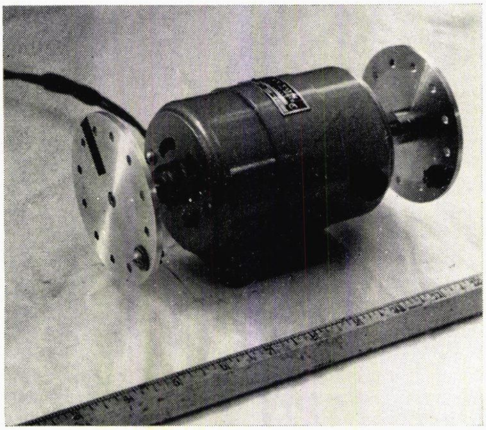

Figure 3. Motor with unbalanced weights attached to discs.

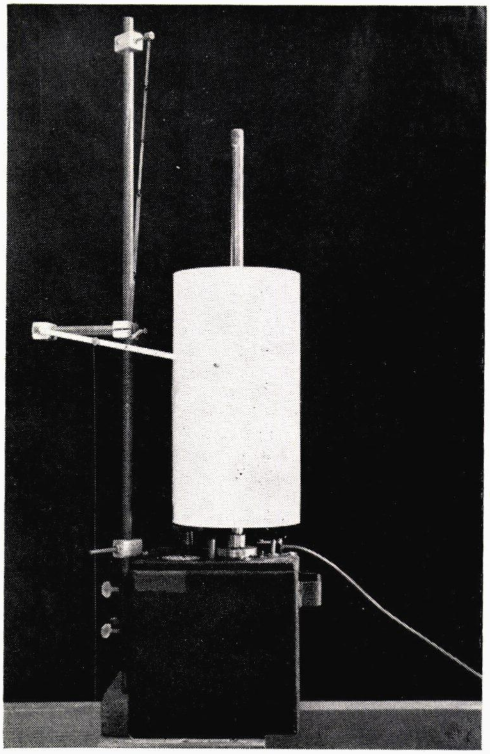

Figure 4. Constant-speed drum for recording penetration against time.

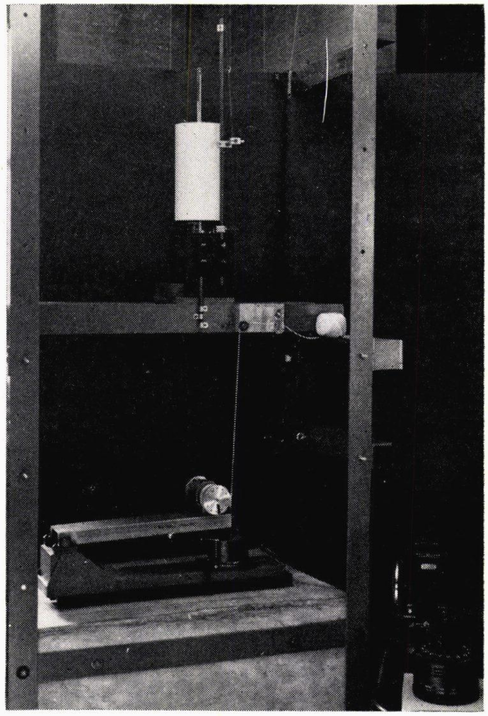

Figure 6. Overall view of single-degree-of-freedom apparatus for penetration tests, showing cutting apparatus on concrete pier and recording drum mounted above it.

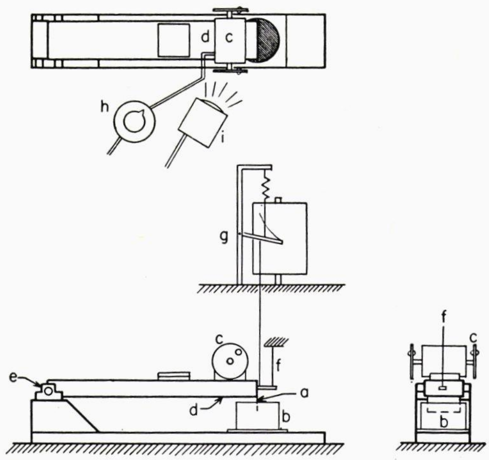

Figure 5. Diagram of single-degree-of-freedom apparatus for penetration tests: *a*. Blade; *b*. Container; *c*. Motor and unbalanced discs; *d*. Cutting head beam; *e*. Rigidly mounted bearings for cutting head beam; *f*. Release string; *g*. Recorder; *h*. Variable transformer; *i*. Stroboscope.

as follows: The cutting head is suspended by a string so that the cutting edge of the blade is in contact with, but not resting on, the soil. The speed of the motor is then adjusted to the desired steady value, and the string is cut, releasing the cutting head and allowing the blade to penetrate the soil under the influence of the static and dynamic load components. In the slicing tests, the blade is inserted into the soil immediately before the start of the test. The motor is then adjusted to the desired speed and the static pulling force applied to the cutting head carriage.

The static load tests are carried out in the same manner as the dynamic except that the unbalances are not rotated. The entire static load is applied to the cutting head prior to releasing the blade. No changes are made in the load after the blade has been released.

The apparatus has been shown in Figures 1 to 12.

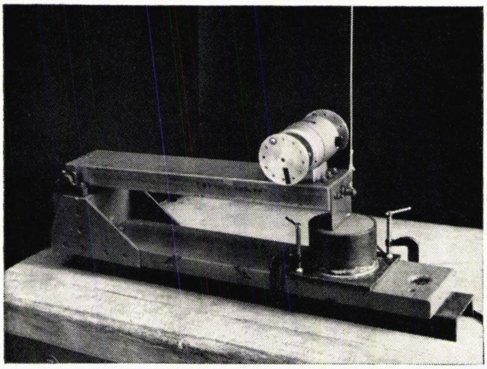

Figure 7. Details of cutting head beam and bearing supports, motor and discs, blade, and container; single-degree-of-freedom apparatus for penetration tests.

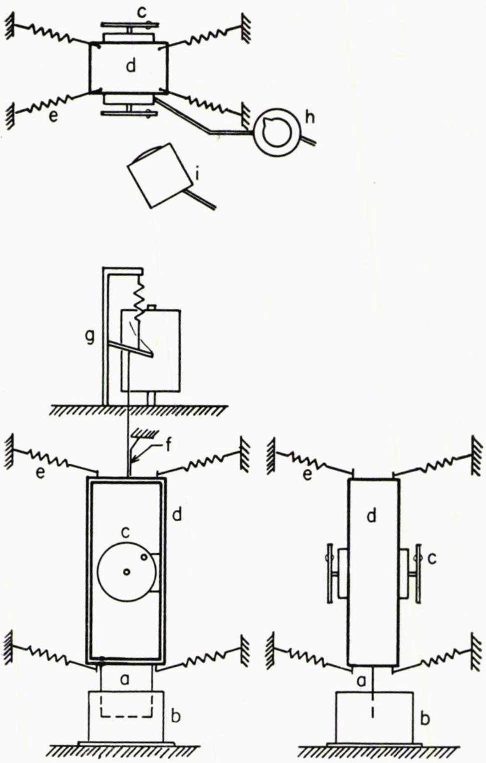

Figure 8. Diagram of 6-degree-of-freedom apparatus for penetration tests: *a*. Blade; *b*. Container; *c*. Motor and unbalanced discs; *d*. Cutting head frame; *e*. Suspension springs for cutting head frame; *f*. Release string; *g*. Recorder; *h*. Variable transformer; *i*. Stroboscope.

"SOIL" TYPES

Three types of materials were investigated, including a sand, a silty clay, and Plasticene, which is an artificial material resembling clay

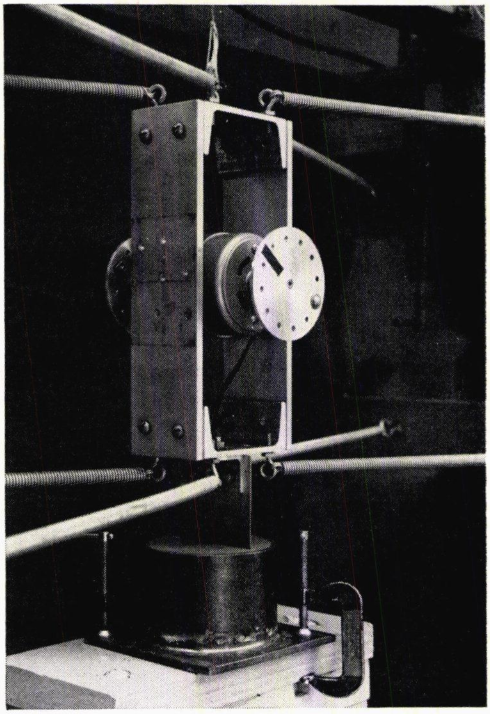

Figure 9. Details of cutting head frame and spring suspension, motor and discs, blade, and container; 6-degree-of-freedom apparatus for penetration tests.

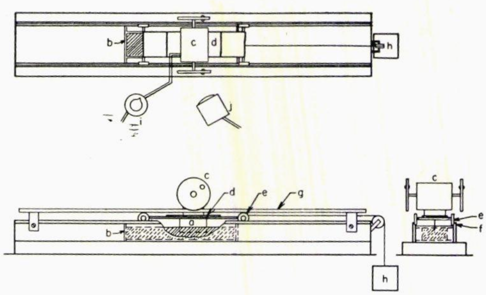

Figure 10. Diagram of 3-degree-of-freedom apparatus for slicing tests: *a*. Blade; *b*. Container; *c*. Motor and unbalanced discs; *d*. Cutting head carriage; *e*. Carriage wheels; *f*. Track; *g*. Reaction bars to eliminate tipping of carriage due to unbalanced moment created by driving force and by soil reaction; *h*. Driving load; *i*. Variable transformer; *j*. Stroboscope.

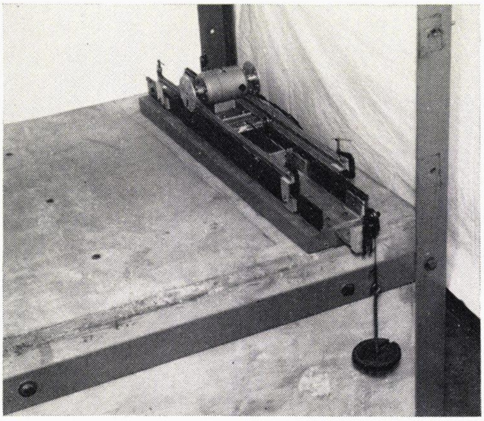

Figure 11. Overall view of 3-degree-of-freedom apparatus for slicing tests. (The apparatus is rigidly bolted to the concrete pier during tests.)

in some of its properties. Plasticene, because of the relatively constant nature of its properties and the ease of handling, was used during the development of the cutting apparatus. Complete tests of the sand and of the clay were made only on the single-degree-of-freedom penetration apparatus. The properties of the materials are as follows:

Plasticene

An oil base, fine particle, cohesive plastic; considerably sensitive to temperature change; results plotted for a standard temperature of 70°F.

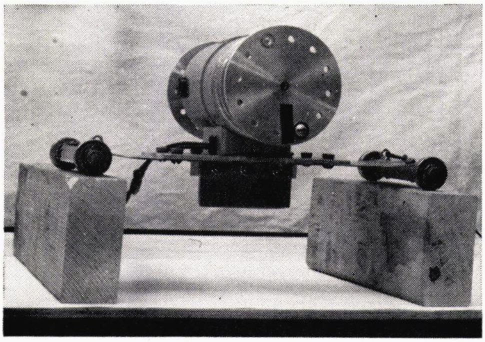

Figure 12. Details of cutting head carriage and wheels, motor and discs, and blade; 3-degree-of-freedom apparatus for slicing tests.

Silty Clay

"Liquid limit," 47.6 percent moisture; "plastic limit," 27.8 percent moisture; unless otherwise shown, the results have been plotted for a moisture content equal to the plastic limit.

Sand

A well graded sand passing a No. 20 sieve and containing about 10 percent fines passing a No. 200 sieve; "optimum moisture content," 9.5 percent; unless otherwise shown, the results have been plotted for a moisture content equal to the optimum.

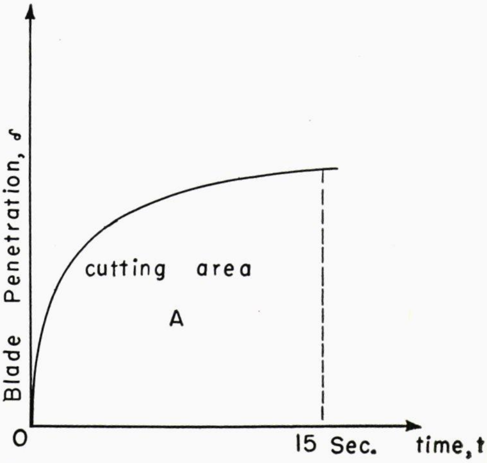

Figure 13. A typical curve of blade penetration versus time, for the penetration apparatus.

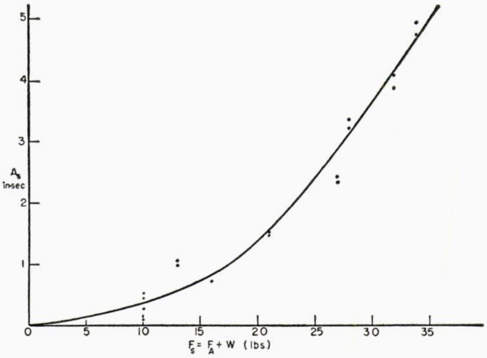

Figure 14. Static loading of penetration blade in Plasticene; cutting area A_S versus total cutting force F_S. Single-degree-of-freedom penetration apparatus; static tare weight, W = 10.25 pounds; temperature 70°F.

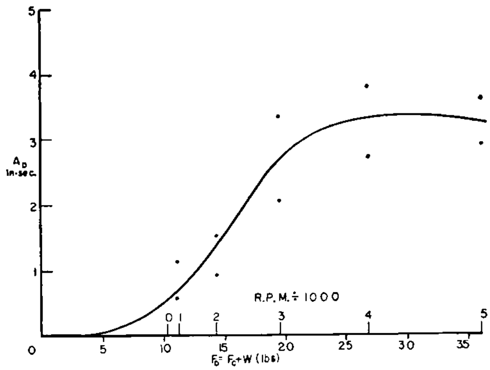

Figure 15. Dynamic loading of penetration blade in Plasticene; cutting area A_D versus total cutting force F_D. Single-degree-of-freedom penetration apparatus; static tare weight, W = 10.25 pounds; rotating unbalance wr = 0.0364 lb. in.; temperature 70°F.

RESULTS OF PENETRATION TESTS USING SINGLE-DEGREE-OF-FREEDOM APPARATUS

Basis for Comparison of Static and Dynamic Cutting

A typical curve of blade penetration versus time, for the penetration apparatus, has been shown in Figure 13. The penetration-time curves for the static and for the dynamic loadings are much alike in shape. A logical quantity to use as the basis for comparison is the area under the curve for a specified constant duration of cutting. A duration of 15 seconds was found to be satisfactory for most test conditions and was therefore adopted as a standard.

Symbols

The symbols are as follows:

A_S and A_D = proportional to area under penetration-time curve ("cutting area") for a duration of 15 seconds; subscript S for static loading, D for dynamic; dimensions are *inch-seconds* (penetration × time).

W = static tare weight at blade, including cutting head, motor, discs, etc.

F_S = F_A + W = total cutting force at blade; static loading.

F_A = increment of static load added to tare weight.

F_D = $F_C + W$ = total maximum cutting force at blade; dynamic loading.

F_C = $wr\omega^2/g$ = centrifugal force created by rotating unbalance.

w = total weight of unbalance attached to discs.

r = radius of rotation of unbalanced weights.

g = acceleration of gravity.

ω = angular velocity of discs (forcing frequency), radians/second,

$$\omega = \frac{2\pi}{60} \times (\text{rpm}).$$

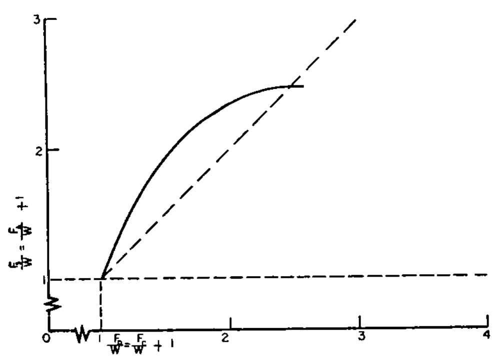

Figure 16. Total static cutting force versus total dynamic cutting force, for equal areas of cutting; Plasticene. Derived from Figures 14 and 15. Single-degree-of-freedom penetration apparatus; static tare weight, W = 10.25 pounds; rotating unbalance, wr = 0.0364 lb. in.

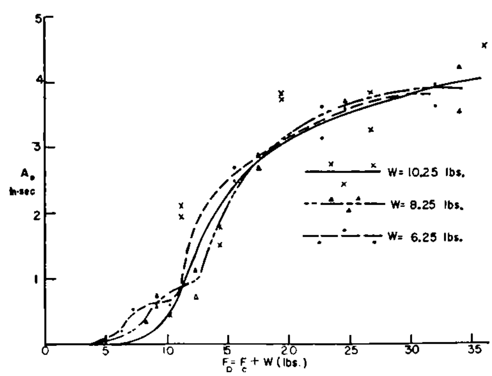

Figure 17. Effect of variation in tare weight. Cutting area A_D versus total cutting force F_D; single-degree-of-freedom penetration apparatus; Plasticene; rotating unbalance, wr = 0.0364 lb. in.

Tests on Plasticene

Comparison of Static and Dynamic Cutting. Plots of "cutting area" against total cutting force have been shown in Figures 14 and 15 for static and for dynamic loading, respectively.

If now we determine from the curves in Figures 14 and 15 the total cutting forces, F_S and F_D, required to produce equal cutting areas, $A_S = A_D$, and plot these forces in dimensionless form, F_S/W and F_D/W, as ordinate and abscissa, we arrive at the curve shown in Figure 16. This is the curve of total static cutting force versus total dynamic cutting force, for equal areas of cutting.

The difference between the total cutting force for static loading and the total maximum cutting force for dynamic loading is not great. However, a definite possibility of advantage in the use of dynamic loading is evident if one considers that the static load increment F_A represents an addition of dead weight, or by implication, increased "draw-bar force," while the dynamic load increment F_C is produced merely by revolving the unbalance.

Tare Weight. The effects of variation in tare weight, within the range tested, are not of much consequence, as shown by Figure 17. However, it is thought that either very small or very large tare weights would be undesirable.

Unbalanced Moment and. Rotation Speed. The unbalanced centrifugal force is directly proportional to the first power of the un-

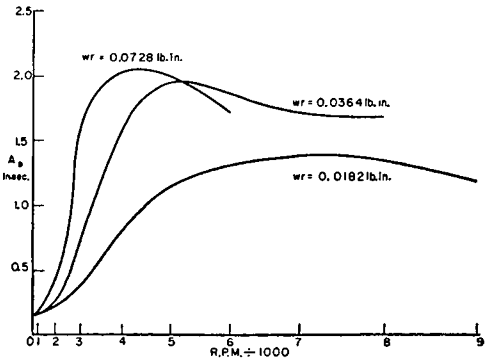

Figure 18. Effect of variation in unbalanced statical moment and in rotation speed. Cutting area A_D versus rotation speed (forcing frequency); single-degree-of-freedom penetration apparatus; Plasticene.

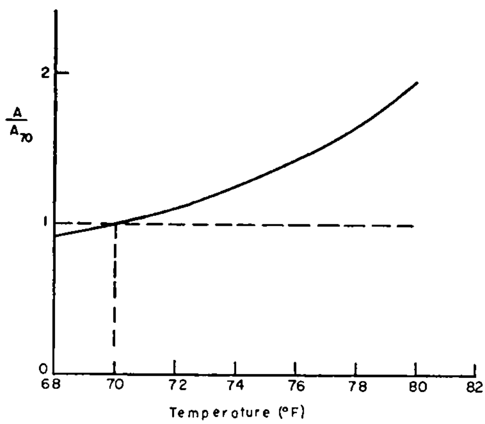

Figure 19. Effect of variation in temperature of Plasticene. Single-degree-of-freedom penetration apparatus.

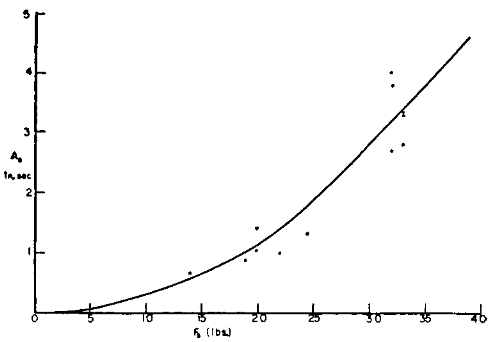

Figure 20. Static loading of penetration blade in silty clay; cutting area A_S versus total cutting force F_S. Single-degree-of-freedom penetration apparatus; static tare weight, W = 6.25 pounds; moisture content at plastic limit.

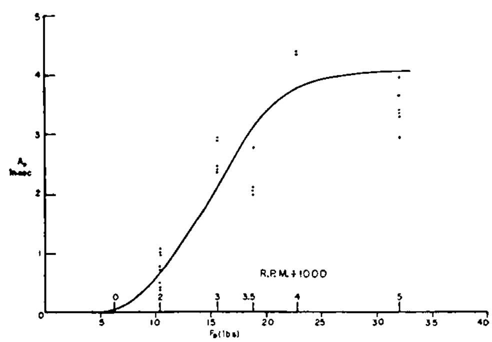

Figure 21. Dynamic loading of penetration blade in silty clay; cutting area A_D versus total cutting force F_D. Single-degree-of-freedom penetration apparatus; static tare weight, W = 6.25 pounds; rotating unbalance, wr = 0.0364 lb. in.; moisture content at plastic limit.

balanced statical moment and directly proportional to the square of the frequency. The effect of varying both of these quantities independently has been shown in Figure 18. There is no apparent evidence of the existence of critical or resonant frequencies. The forcing frequencies are far below the natural frequencies of the blade. Considerable attention was paid to the elimination of possible resonance effects in the cutting head, supports, and container. (Apparatus which will provide very-high-frequency excitation, and which will make it possible to excite resonances in the cutting blade, is under development.)

Temperature. It has already been mentioned that Plasticene is considerably sensitive to temperature. A normalized temperature correction curve, based on many tests, both static and dynamic, with total cutting forces ranging from 10 to 36 pounds and with temperatures ranging from 68°F to 82°F, has been shown in Figure 19. The ordinate is the ratio of cutting area to the reference cutting area at 70°F. It is evident that a temperature increase may result in a considerable increase in the rate of cutting.

Tests on a Silty Clay

Comparison of Static and Dynamic Cutting. Figures 20 and 21 show plots of cutting area against total cutting force for static and for dynamic loading. The tests were made at the "plastic limit." It will be noticed that there is a considerably greater spread in the results for a given magnitude of load than in the case of the artificial material, Plasticene. This is

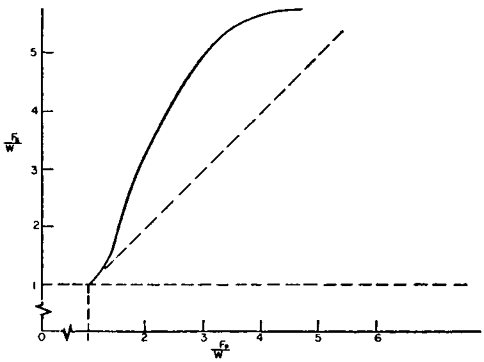

Figure 22. Total static cutting force versus total dynamic cutting force, for equal areas of cutting; silty clay. Derived from Figures 20 and 21.

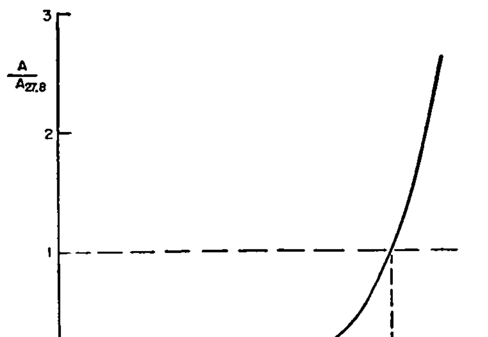

Figure 23. Effect of variation in moisture content of the silty clay. Single-degree-of-freedom penetration apparatus. Plastic limit = 27.8%; Liquid limit = 47.6%.

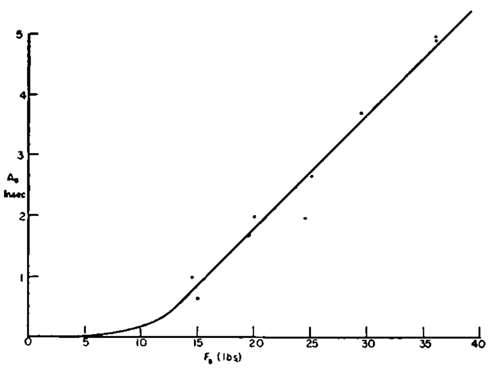

Figure 24. Static loading of penetration blade in sand; cutting area A_S versus total cutting force F_S. Single-degree-of-freedom penetration apparatus; static tare weight, W = 6.25 pounds; optimum moisture content.

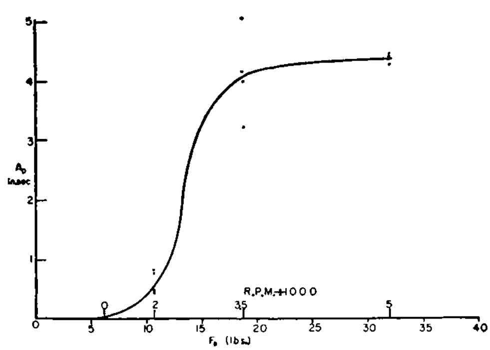

Figure 25. Dynamic loading of penetration blade in sand; cutting area A_D versus total cutting force F_D. Single-degree-of-freedom penetration apparatus; static tare weight, W = 6.25 pounds; rotating unbalance, wr = 0.0364 lb. in.; optimum moisture content.

not unexpected, considering the greater variation in the properties of the natural clay.

The curve in Figure 22 is the curve of total static cutting force versus total dynamic cutting force, for equal areas of cutting. It is derived from Figures 20 and 21 in the same manner that the curve in Figure 16 has been derived from Figures 14 and 15. Note that the tare weight has been made smaller than for the tests on Plasticene.

Moisture Content. The clay is of course very sensitive to moisture content. Figure 23 shows a correction curve for moisture content, based on many tests, static as well as dynamic, with rotation speeds varying from 2000 to 5000 rpm, with total cutting forces ranging from 10 to 30 pounds, and with moisture content ranging from 2 to 35 percent. The ordinate is the ratio of cutting area to the reference cutting area at the plastic limit. The curve shows nearly zero cutting in the moisture content range of 10 to 18 percent. However, cutting would presumably occur in this range if the forces were great enough. Time did not permit a more complete investigation of the effect of moisture content. It is apparent, however, that the moisture content is an important variable.

Tests on a Sand

Comparison of Static and Dynamic Cutting. Curves of cutting area against total cutting

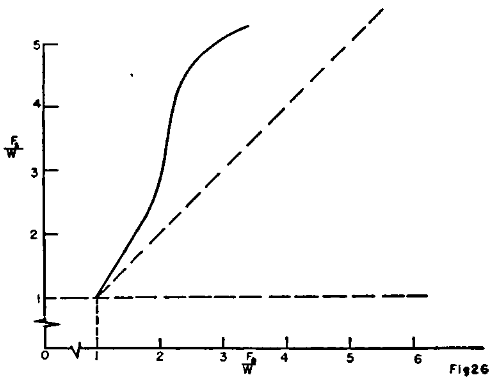

Figure 26. Total static cutting force versus total dynamic cutting force, for equal areas of cutting; sand. Derived from Figures 24 and 25.

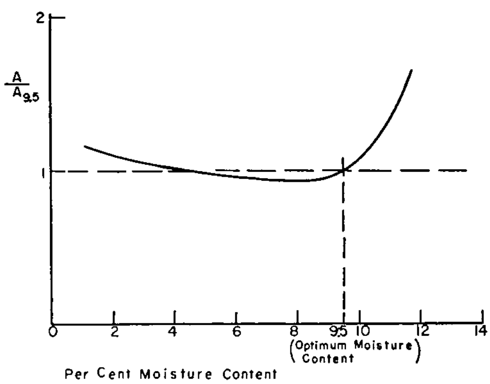

Figure 27. Effect of variation in moisture content of the sand. Single-degree-of-freedom penetration apparatus. Optimum moisture content = 9.5%.

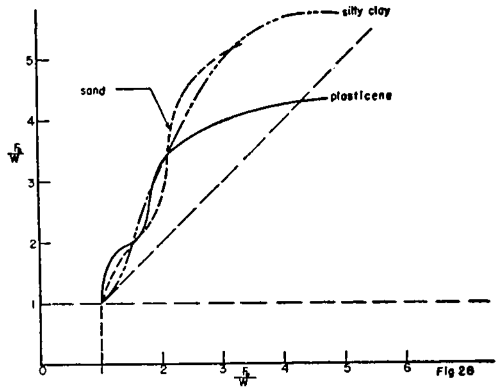

Figure 28. Comparison of penetration tests on Plasticene, silty clay, and sand. Total static cutting force versus total dynamic cutting force for equal areas of cutting. Plasticene at 70°F., clay at plastic limit, sand at optimum moisture content. Single-degree-of-freedom penetration apparatus; tare weight, W = 6.25 pounds; rotating unbalance, *wr* = 0.0364 lb. in.

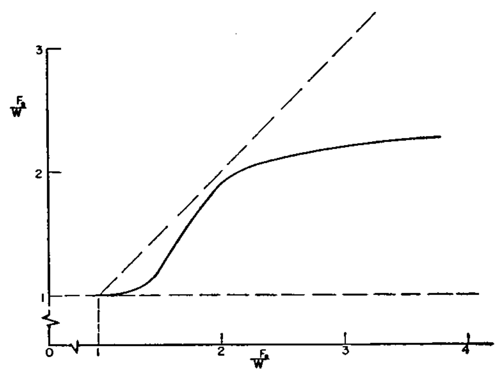

Figure 29. Total static cutting force versus total dynamic cutting force, for equal areas of cutting; Plasticene. Six-degree-of-freedom penetration apparatus; static tare weight, W $\approx$ 9.2 pounds; rotating unbalance, *wr* = 0.0364 lb. in.

force for static and for dynamic loading have been shown in Figures 24 and 25. The tests were made at the "optimum moisture content." Figure 26 shows the curve of total static cutting force versus total dynamic cutting force for equal areas of cutting. The tare weight is the same as for the tests on the silty clay.

Moisture Content. The sand is sensitive to moisture content but considerably less so than the clay. A moisture content correction curve has been shown in Figure 27. It is based on both static and dynamic tests; however, the dynamic tests were limited to a moisture content ranging from 8.5 to 10 percent.

Comparison of Tests on Plasticene, Silty Clay, and Sand

Curves of total static cutting force plotted against total dynamic cutting force for equal areas of cutting have been shown in Figure 28 for Plasticene, silty clay, and sand. The tare weight is constant. There is surprisingly little difference between the curves for clay and for sand. Static force advantage ratios, W/F_S, smaller than $1/5$, are evident. The force advantage ratio is the ratio of the static force that drives the dynamically excited cutting head to the static force required to perform an "equal measure" of cutting without dynamic excitation.

RESULTS OF PENETRATION TESTS USING SIX-DEGREE-OF-FREEDOM APPARATUS

Comparison with Single-Degree-of-Freedom Apparatus

The 6-degree-of-freedom apparatus generally proved to be a less efficient cutting device than the single-degree-of-freedom apparatus, probably due to the greater opportunity for energy dissipation in unproductive motion. The restraint of a practical device constructed for use in the field would be some place between the two extreme types of restraint tested in the laboratory. As far as the purpose of the laboratory is concerned, the single-degree-of-freedom device is superior because it is easier to construct and is much easier to control.

Figure 29 shows, for Plasticene, a curve of total static cutting force against total dynamic cutting force for equal areas of cutting. If the curve is compared with the one in Figure 16, it will be found that dynamic loading shows greater advantage in the single than in the 6-degree-of-freedom apparatus.

Orientation of Planes of Dynamic Forces

In the tests reported in Figure 29 the orientation of the unbalanced driving discs with respect to the cutting blade was the same as in the tests with the single-degree-of-freedom apparatus. One of the purposes of the 6-degree-of-freedom device was to investigate the effect of changing the orientation of the dynamic exciting forces. The plane of the blade and the direction of penetration were vertical. The orientations of the planes (discs) of the exciting forces included the following: (1) vertical and perpendicular to the plane of the blade (as in all of the tests already described); (2) vertical and parallel to the plane of the blade; (3) inclined at 45° and perpendicular to the plane of the blade; and (4) horizontal. The first orientation generally showed the greatest advantage; however, the differences usually were not great and it is not believed worthwhile to report on the long series of experiments on orientation.

Tests in which the blade was made more flexible, (1) by reducing its thickness by one-half, and (2) by greatly increasing its length in the direction of cutting, did not result in significant differences.

Since the 6-degree-of-freedom apparatus did not lead to conclusions significantly different from those developed by the single-degree-of-freedom device, the investigation of materials other than Plasticene was not pursued.

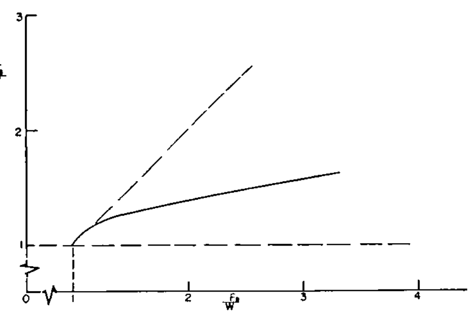

Figure 30. Total static cutting force versus total dynamic cutting force, for equal time durations of cutting; Plasticene. Three-degree-of-freedom slicing apparatus; static tare weight, W = 10 pounds; rotating unbalance, wr = 0.0364 lb. in.

RESULTS OF SLICING TESTS USING THREE-DEGREE-OF-FREEDOM APPARATUS

The slicing-test apparatus proved to be far less efficient in cutting than either of the penetration devices and much more difficult to use. However, it is felt that the poor efficiency is due to the design of the apparatus rather than to any basic fallacy in the application of dynamic loading. The results have been given in Figure 30 where the total static cutting force has been plotted against total dynamic cutting force for equal times required to slice through a specified length. Plasticene was the only material investigated.

CONCLUSIONS

1. As far as can be determined by the small-scale laboratory tests, the use of dynamic loading in conjunction with a static load is advantageous in the cutting of some soils. Static force reductions as great as 1 to 5 have been found for a clay (at the plastic limit) and for a sand. The advantage lies in the reduction of the weight of weight-loaded cutting devices, and, by implication, in the reduction of "draw-bar" force in the case of power-driven cutting blades.

2. A feasibility study for full-scale application in the field would require additional tests at large scale and an economic study of initial cost, maintenance, and operation.

3. No attempt was made to excite resonant vibrations of the cutting blade and resonance does not appear to be essential to the effective use of dynamic loading. However, resonant excitation should be investigated for possible greater effectiveness. Laboratory equipment is now being constructed for use in a study of resonance effects.

4. The dynamic loads consist of unbalanced centrifugal forces that may be generated by apparatus of a type that is simple and readily available either in the laboratory or in the field.

5. An interesting by-product of the investigation is the close resemblance, in behavior under the tests, of the artificial material Plasticene and of the silty clay.

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