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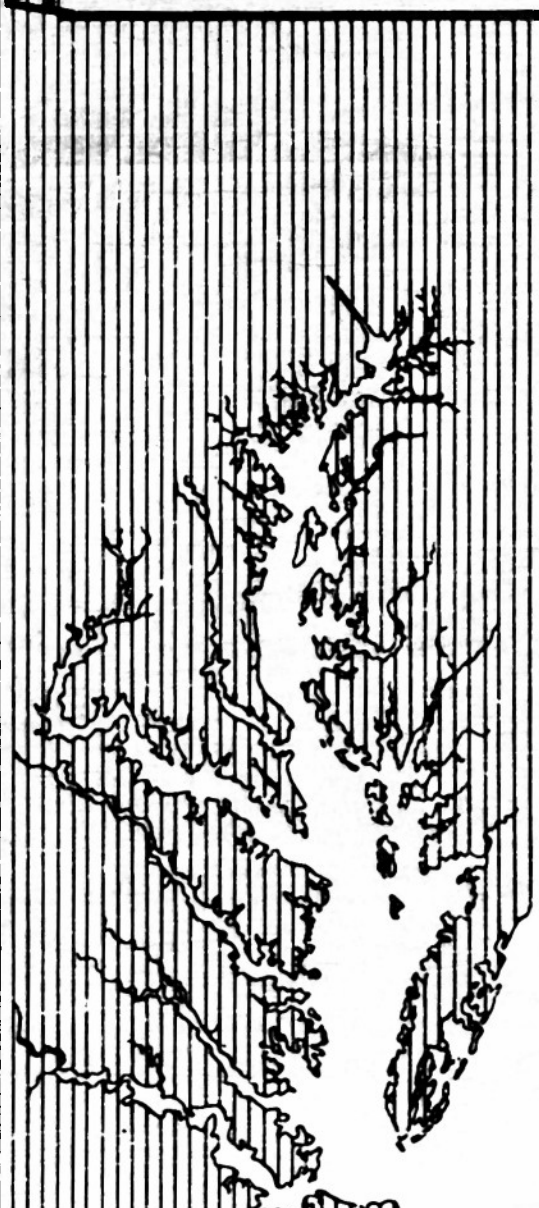

A New Type Penetrometer for Measuring Certain Soil Properties
Special Report 2

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CHESAPEAKE BAY INSTITUTE
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SPECIAL REPORT NO. 2

A NEW TYPE PENETROMETER FOR MEASURING CERTAIN SOIL PROPERTIES

By

M. C. Powers

This report contains results of work carried out for the Office of Naval Research of the Navy Department under Project NR 084-005, Contract Nonr-248(07), and Project NR 083-070, Contract Nonr-248(30), and for the U. S. Navy Hydrographic Office.

Reference 52-24
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Director

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ABSTRACT

A penetrometer is described which measures a combination of physical and chemical properties of underwater sediments. The measure is called rigidense (Rd.) and the measuring device is called a rigidense instrument. Curves are given which show the relation of water content to rigidense for clays, silts, sands, and mixtures of these materials. Curves based on the plastic properties of some clay minerals and curves based on size distribution of sand are discussed.

The rigidense instrument is used in the field to measure the compaction and bearing capacity of sediments. It is used in the laboratory to study the physical and chemical properties of sediments.

INTRODUCTION

The Chesapeake Bay Institute has begun a study to determine the physical properties of the Chesapeake Bay sediments, particularly the stability characteristics of the first ten feet, and how these properties affect the sinking of mines. Most of the field work has been done aboard the Chesapeake Bay Institute research vessel MAURY. A Kullenberg piston-type coring gear modified by CBI personnel was used to obtain cores (Silverman, Maxwell and Whaley, Richard C., 1952).

The term stability as used here means the ability of a sediment to resist deformation by loads imposed by mines. The factors influencing sediment stability in the Chesapeake Bay are manifold. Table I lists most of the important ones. It would be impractical to attempt the measurement of each with the object of relating it to the stability characteristics. For this reason the rigidense instrument was developed to obtain a numerical measurement of the combined effect of these factors. Each of the factors listed will eventually be studied in the field and in the laboratory,

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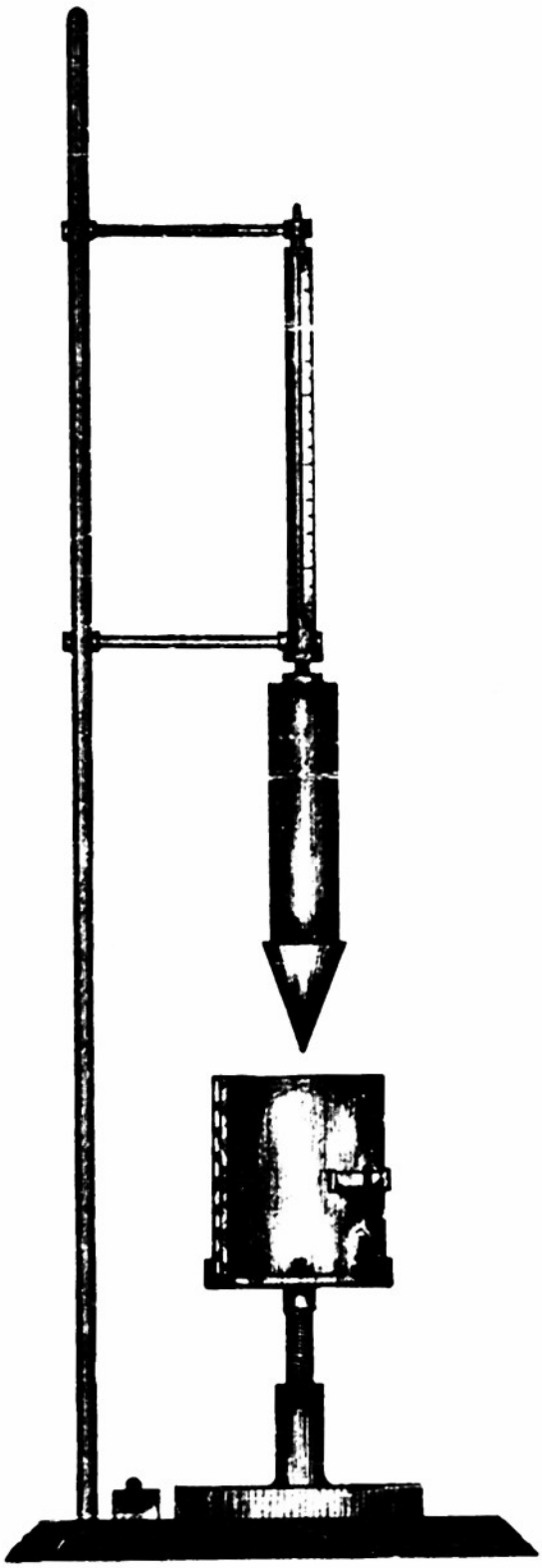
and an attempt will be made to determine their relation to mine sinking problems.

TABLE I

FACTORS AFFECTING THE STABILITY OF SEDIMENTS

1. Partial size analysis
   The following 4 grade sizes should be measured:
   a. Clay (less than 0.0039 mm).
   b. Silt (0.0039 - 0.062 mm).
   c. Sand (0.062 - 2.0 mm).
      (including sieve analysis corresponding to the Wentworth grade scale).
   d. Gravel (greater than 2.0 mm).
2. Types of clay.
3. Amount of amorphous material.
4. Exchangeable ions present.
   (organic and inorganic)
5. Natural water content.
6. Wet density
   (also called wet unit density or lump density).
7. Organic carbon
   (amount and nature).
8. Biological activity
   (amount and nature).
9. Cations and anions in solution
   (ones forming an important part).
10. Erosional stability of the sediments.
11. Compositional stability of the sediments.
12. Miscellaneous factors:
    a. Gas bubbles (if large and plentiful).
    b. Worm holes.
    c. Shell content (including decompositional state of the shells).
    d. Roundness and sorting of sand size fractions.
    e. Peat or other vegetable remains.
    f. Directional movement and salt content of intergranular water in the sediment.
    g. pH and redox potential of the sediment.
    h. Traction zone thickness*.

*A discussion of this property will appear in a forthcoming paper.



Rigidense Instrument

GENERAL PROPERTIES OF SEDIMENTS

If nothing else were known about a sediment, the proportion of sand, silt, and clay would give a general indication of the stability of the system (Trask, P.D. and Rolston, J.W., 1951). However, the relation of grain size to stability becomes unreliable when carried more than a foot or so below the bottom surface, since below this depth water may be squeezed out of clay materials and the water system in the sediments may lack vertical homogeneity. Only in the case of clean sands can the relation be extrapolated to any great depth. Sand will absorb only a limited amount of water, depending on sorting, angularity, and the type of packing prevalent. It will be shown that there is a limit to the effect produced by the addition of water only in the case of clean sand.

Increase in the clay-size content of a sediment generally increases the possibility of flowage, compression, and shear failure. Usually two or more clays exist in sediments. They may be of the montmorillonoid, micaceous, kaolinitic, allophane, or rock flour types. Allophane is common in most sediments.

The difference in properties exhibited by clays is usually explained as a result of differences in their atomic structure. Kaolinitic clays have a two-layered structure with the crystals held together by a oxygen-hydroxyl bond while montmorillonitic clays are three-layered and oxygen-oxygen bonded. From this it can be inferred that a montmorillonoid is more easily separated than a kaolinite. Among other things, this difference in structure between the clay minerals partially accounts for the higher base exchange capacity in montmorillonoids. Illite, also a three-layered clay, may have either the properties of a typical bentonite or properties intermediate between those of kaolinite and of montmorillonite. Solely on the conditions of the

bonding properties of the clays it is easy to see that they would have quite different water properties. The water properties of a three-layered clay vary with the interlayer atoms and their structural relation to each other (Grim, R. E. and Cuthbert, F. L., 1945).

It has been shown by Grim and others including the author, that as little as 5 percent by weight of a montmorillonoid may have very pronounced effects on the water properties and hence on most of the physical properties of a sediment-system. It is reasonably safe to say that anomalies in the natural water content of a sediment depend almost wholly on the type and amount of clay present and on the exchangeable ions. Knowledge of the sorting coefficient alone will tell very little about the water absorption capacity of a sediment. Wet density is profoundly affected by clay content for at least three reasons: (1) As the clay content increases so does the natural water content; (2) Clays have a very wide range in specific gravity; (3) The organic matter present seems to vary directly as the clay content. Each of these three properties will depend on the type clay and exchangeable ions.

The plasticity of a sediment generally increases with the clay content. Cassagrande's liquid limit and plastic limit show that montmorillonite has a much greater plastic range than kaolinite or most forms of illite, and that the plastic range is affected by the exchangeable ions. Liquid limit and plastic limit, however, do not measure the entire plastic range of clay sediments. There are no accurate measurements of the thresholds where a solid substance begins to act as a plastic material, and where a plastic substance begins to act as a liquid. If liquid limit and plastic limit are thought of only as the water content at certain characteristic physical disturbances, the terms become quite valuable and may be used as indicators for observed geologic phenomena.

In dealing with the problem of the settling of mines into marine or fresh water bottom sediments, it is of utmost importance to determine first of all whether one is concerned with consolidation, shear failure, or flowage. In the case of mines, particularly air dropped mines, it is likely that very little consolidation or shear failure results from the load. Sinking seems to be related to a flow phenomena or what is sometimes known as "high speed shear." For this complex problem the standard measurements perfected by soil mechanics, such as consolidation, quick shear, direct shear, and confined and unconfined compression tests, do not appear to be of value. The investigator must work out and understand the cohesive and frictional properties of sediments, and the relation of these properties to objects of known volumes and densities. Impact velocity must also be taken into account. Immediately one sees the importance of a test which would be a measure of the overall chemical-physical properties of a sediment and the importance of relating such a measurement to field observations. If such a relation could be obtained, it would then become possible to relate each property listed in Table I to stability and also to each other. For instance, one may discover that 5 percent organic carbon completely unstabilized a montmorillonitic sediment; whereas the same amount of organic carbon had an entirely different effect on kaolinitic sediments (Grim, R. E., et.al., 1947). Further, it may become possible to predict the stability of a sediment at a given water content from the clay mineral types, amounts, and other factors. Most important, once the interrelations of these properties are known, stability estimates for remote regions could be made from minimum information.

Cassagrande's liquid limit has been used in an attempt to fulfill the requirements of such a test. However, the author prefers to use Cassagrande's machine to

determine the number of blows necessary to close the groove at the natural water content of the sediment rather than determine the liquid limit as defined by Casagrande and others. The 25 blow line becomes meaningless for stability studies as defined here unless one can relate this value to the natural water content of the sediment. For underwater, near surface sediments in Chesapeake Bay the natural water content is generally very much greater than liquid limit. The number of blows required to close the groove is an empirical measurement, and according to Casagrande (Casagrande, A., 1932), a shear phenomenon.

With this point and those cited earlier in the paper in mind, a rather simple penetrometer has been constructed and called a rigidense instrument.

DESCRIPTION OF THE RIGIDENSE INSTRUMENT

The rigidense instrument consists of a ring stand, two leveling bubbles, a brass sample container, an adjustable brass base to support the container, and a lead penetrometer weight with attached brass millimeter scale. Figure 1 is a drawing of the entire assembly.

An aluminum cone with a vertex angle of 37 degrees fits the base of a lead weight which is 2 cm in diameter and 11 cm long. There is a brass millimeter scale attached to the top of the lead penetrometer. Total weight of the lead weight, aluminum cone, and brass scale is 435 grams. A slide lock holds the penetrometer in rest position, at which point the millimeter scale reads zero flush with the top surface of the guide ring.

The sample container is made of 2 mm brass tubing. It is 6.4 cm deep and 4.9 cm inside diameter. A hinge and spring catch allow the cup to be opened and

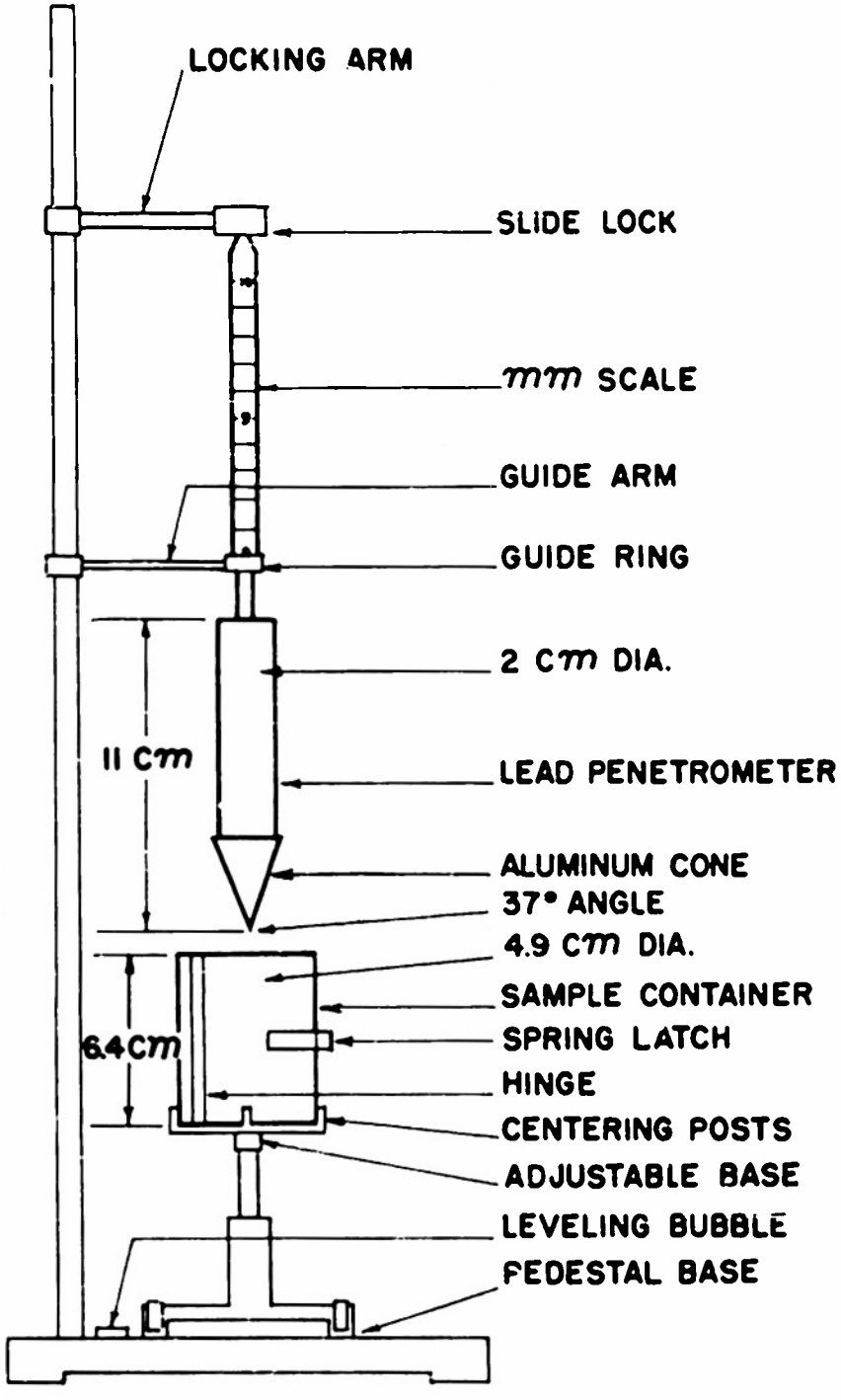


FIGURE 1

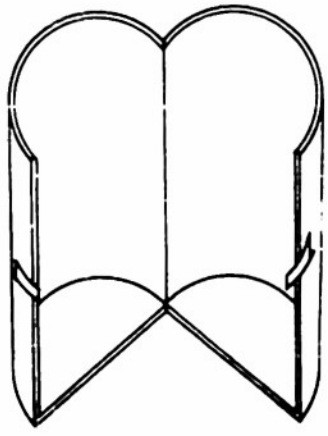


FIGURE 2

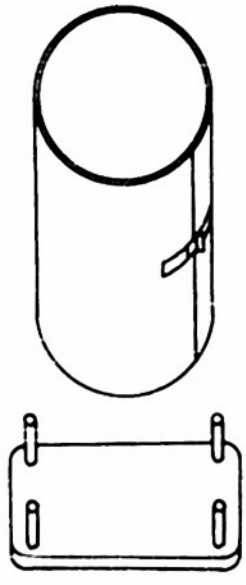


FIGURE 3

closed (Figure 2). This feature is incorporated in the cup to facilitate loading and unloading the sample material. The surface of the sample should be smoothed as little as possible while loading.

A pedestal consisting of a brass fixed base and an upper adjustable stool is provided. The cup is held in place by four centering posts (Figure 3).

After the cup is filled with sample material it is placed on the adjustable base and raised until the penetrometer point just barely touches the surface of the sample. The slide lock is then released and the penetrometer allowed to settle. At the end of two minutes a reading is made in centimeters to the nearest hundredth. In this manner the machine is used to determine the rigidense values (penetration in centimeters) at intervals along a core.

The rigidense machine is designed especially for use on cores. Rigidense values are obtained at intervals along a core as soon as the core is extruded aboard ship. For reproducibility of our results the critical features of the instrument are the total weight of the penetrometer weight, cone, and scale which must be 435 grams, and the vertex angle of the cone which must be 37°.

An attempt is made to preserve the original particle orientation. The author uses a Kullenberg piston-type coring gear which seems to distort mud cores very little when natural water content is below two hundred. Clean sand cores are badly disturbed by the piston action and extruding action imposed on the core. This disturbance is of minor consequence, however, in view of the water properties of sand. Probably 90 percent of the sand in the Chesapeake Bay area shows rhombic, or close packing. The same type of packing occurs in the rigidense cup. Water is often seen to run freely out of a sandy core upon extrusion. This may be neglected as laboratory

tests show that in clean sand, beyond a very small amount of water, further additions do not affect the rigidense values (Figure 4, sand curve). Only in the case of moving water, that is boiling sand or perhaps quick sand, will rigidense values increase beyond a certain point due to increase in the water content.

Since vibration due to the ship's engines causes the weight to settle excessively, the entire rigidense assembly is placed on a large piece of sponge rubber. However, this does not entirely take care of the difficulty and further measures would be advisable. Another important source of error in rigidense values is due to stretching in mud cores caused by piston action.

Significant correlations have been found between rigidense values and the sinking of mines into underwater sediments. These correlations will be published in a later report.

A LABORATORY EXPLORATION OF RIGIDENSE

Aside from impact velocity and weight per unit contact-area, sinking of the penetrometer into an undisturbed sediment is dependent on the properties listed in Table I. In order to find out more about what the measurements obtained with the rigidense instrument mean a series of laboratory experiments were performed.

Samples used in the experiments consisted of the following API reference clays and sand and silt fractions from Chesapeake Bay sediments:

Montmorillonite	Polkville, Miss.
Kaolinite	Macon, Ga.
Illite	Fithian, Ill.
Halloysite	Bedford, Ind.
Sand fractions	Separated from Chesapeake Bay sediments
Silt fractions	Separated from Chesapeake Bay sediments

The clays listed above are described in detail in the API Project 49 publication entitled REFERENCE CLAY MINERALS, 1949.

Relation of natural water content to rigidense

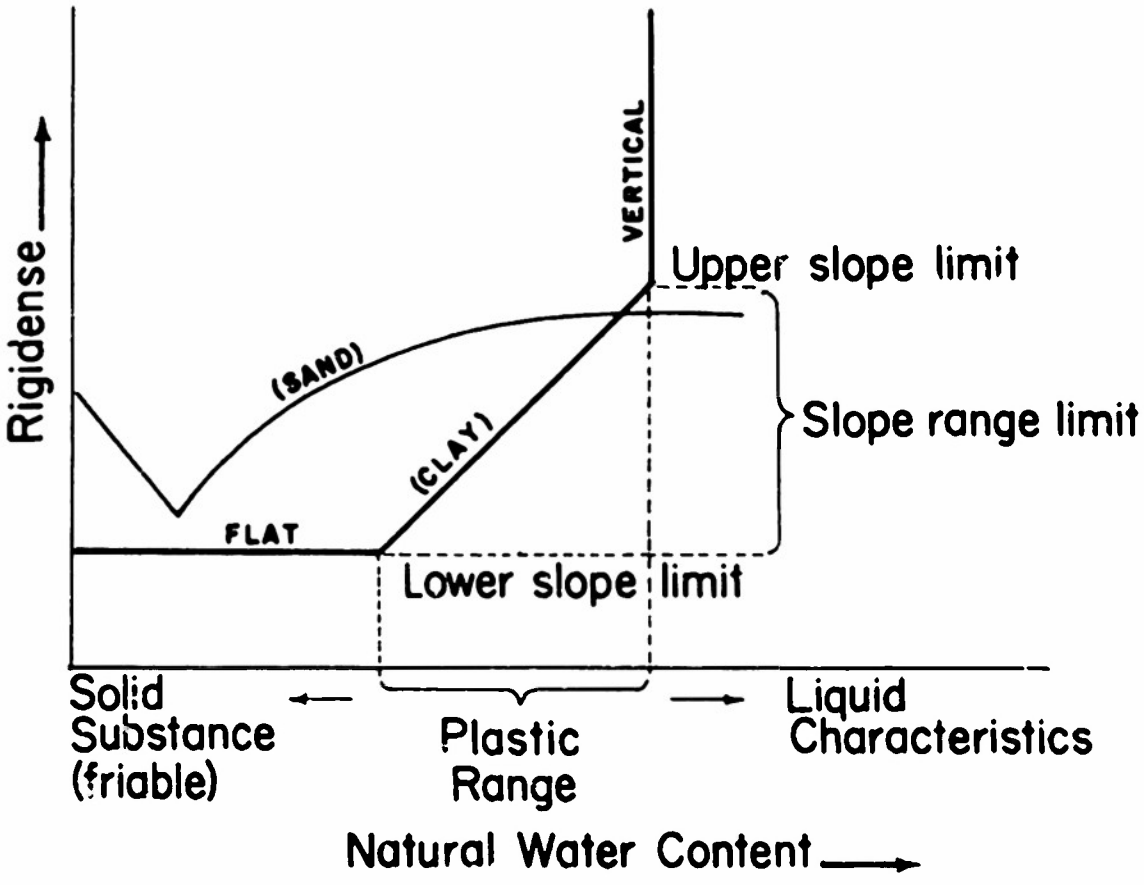


FIGURE 4

Clays and Rd.

The clay, or clays, to be used in an experiment were oven-dried overnight. The sample was then made up by pipetting in the desired amount of water and mixing thoroughly. The water used was about 1N with respect to calcium chloride in order to calcium saturate the clay. Since rigidense is a function of a multitude of physical-chemical properties, it was desired to hold constant properties other than water content. In this way changes in rigidense could be more directly related to changes in water content. The degree of mixing of the water into the sediment was checked by allowing clay-water mixtures to set up to 12 hours after the initial mixing and re-running the tests periodically. The results all agreed very closely indicating proper mixing of water into the samples. At least two test runs were made on split portions of the same sample. The appearance of the sample was recorded after each addition of water. Table II is an example of the log kept during the tests.

TABLE II

EXAMPLE OF LOG KEPT FOR PENETRATION CURVES

SAMPLE: Ga. KAOLINITE (Impurities less than 5%)

% Water	Rigidense		Remarks
(1 and 2)	Sam. 1	Sam. 2	
5	-	-	Dry and crumbly.
10	0.5	0.5	No apparent change.
15	0.6	0.6	Crumbly in balls.
20	0.7	0.6	No apparent change.
25	0.8	0.8	Still crumbly and dry.
30	0.8	0.8	Cannot be worked with spatula, hard when packed.
40	1.6	1.5	Easier to work with spatula, semi-plastic.
45	2.6	2.5	Fairly easy to work with spatula.
50	3.1	3.1	Firm plastic.
55	3.8	3.7	Plastic.
60	4.2	4.4	Slick plastic.
65	5.8+	5.8+	Almost soupy. Did not slow penetrometer at all.

Water content was increased in increments of 5 percent and rigidense determined after each addition of water. The process was continued until the penetrometer sank to the bottom of the cup. These tests were run on montmorillonite, kaolinite, illite, halloysite, silt, sand, and mixtures of these materials. The tests were repeated at least twice, and three times in some cases. Curves were plotted showing rigidense as a function of water content. Figure 5 shows a few of the graphs obtained from the tests. The typical curve consists of a flat initial portion, a sloping middle portion, and what might be termed a vertical terminal portion. This terminal portion is characterized by immediate sinking of the penetrometer to the bottom of the cup (Figure 4, clay curve). This curve, for materials other than sand, is of the same type as those drawn by Scott Blair (Blair, Scott, 1944) in his studies of the plasticity of substances.

The point of change from initial to middle portion seems to occur at a rigidense of 0.5 cm although the water contents are quite different. This point also marks the change from friable to plastic. The middle section is characterized by slope and length and seems to be unique for each mixture. The slope of the line is probably equal to the pseudo viscosity of the system. The more plastic the material the flatter the sloping portion of its rigidense curve and the lower slope limit seems to shift to the right.

The difference in water content between the initial and terminal points of the middle portion is an indication of the plasticity of a material and is called plastic range in this report. As would be expected, the plastic range of montmorillinite is much greater than for kaolinite. The illite and halloysite used in the experiments showed little to no plastic range. When kaolinite and montmorillonite were

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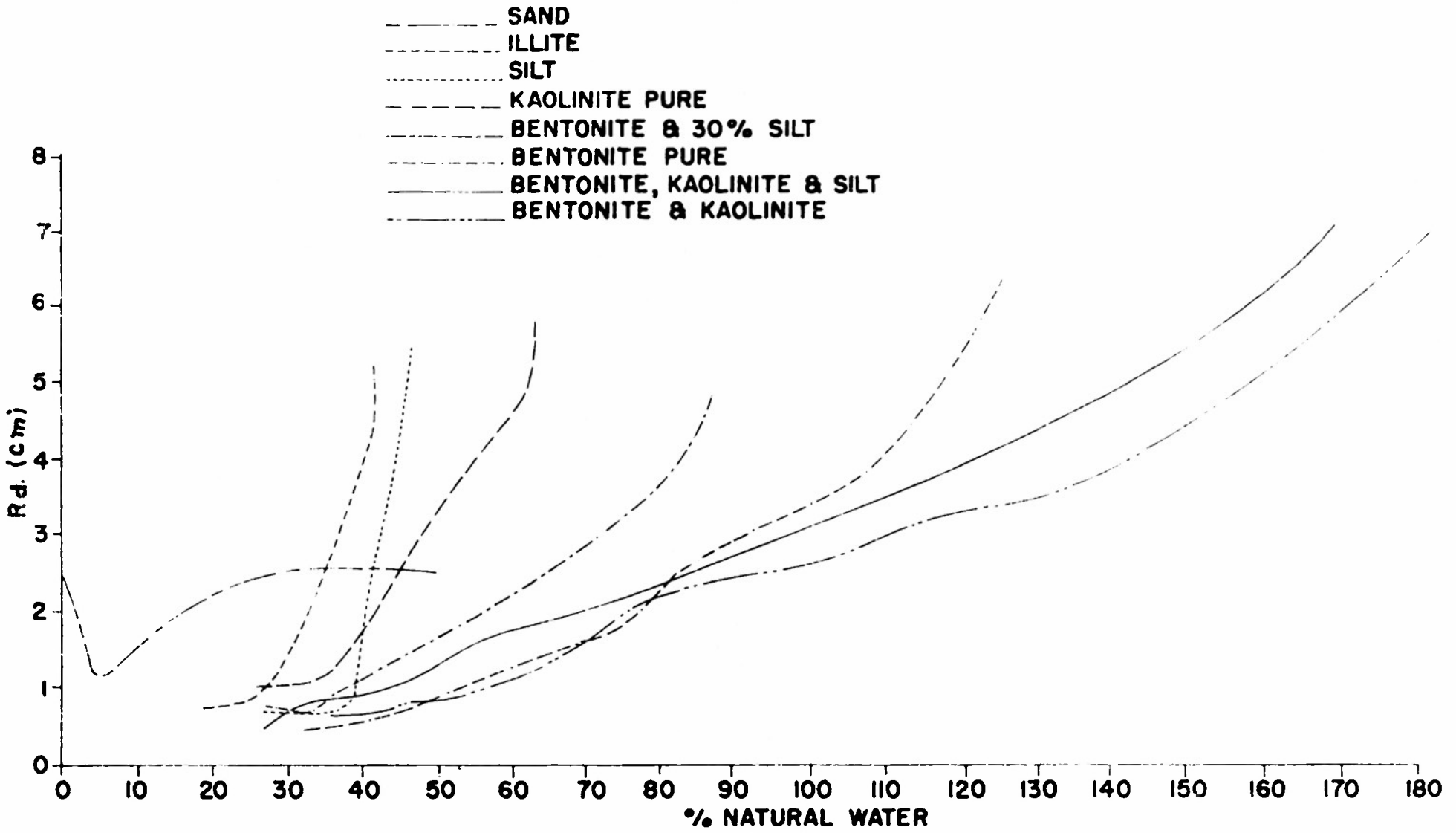

FIGURE 5

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mixed in equal amounts the plastic range far exceeded either montmorillonite or kaolinite alone. It should be noticed that the plastic range of montmorillonite-kaolinite mixture is almost exactly equal to the sum of the plastic ranges of montmorillonite and kaolinite. It may be that the two clays acted independently of each other with respect to water absorption each exhibiting its plastic range at different times. The kaolinite would be likely to absorb water much faster than the montmorillonite. The real reason for the vastly increased plastic range of kaolinite-montmorillonite mixtures is not known at this time.

At the upper slope limit of the curve for any material used, it seems to be almost soupy and undoubtedly is completely unstable as far as supporting capacity is concerned. It should be pointed out that clean coarse sands have no upper slope limit for the weight used.

Silts and Rd.

It is interesting that the silt curve has characteristics of both the clay and sand curves. The primary difference between the silt and sand curves is that the penetrometer ultimately sank completely through the silt but never penetrated beyond a fairly low constant value in sand. The main difference between the silt and clay curves is that the silt curve shows no significant plastic range. The clays which show curves similar to silt, that is with essentially no plastic range, do so because they do not disaggregate readily enough in water to form particles smaller than silt size. It is obvious that particle size affects plasticity as well as do the salts in solution, structure of the crystals, and other factors. It follows therefore that the illite and halloysite curves are similar to the silt curve because they did not disaggregate in water, even after sitting overnight.

Based on the configuration of the water molecules between the unit cells as interpreted by Hendricks and Jefferson (Hendricks, S. B. and Jefferson, M. E., 1938), a monomolecular layer of water in montmorillonite is equal to 0.1 gram of water per gram of clay. Table III gives the computed values for the number of water layers between the unit cells for different mixtures of samples at the lower slope limit. In column A allowance is made for the silt content by assuming that a negligible amount of water is absorbed by the silt. In column B the assumption is made that silt absorbs 40 percent water. This assumption will be discussed further.

TABLE III

WATER LAYERS AT THE LOWER SLOPE LIMIT
FOR VARIOUS CLAY-SILT MIXTURES

% Mont.	% Silt	Rigidense	Water Content	Molecular layers of H_2O on each mont. particle	
				A	B
100	0	0.7	50.0	5.0	5.0
95	5	0.6	45.0	4.7	4.5
87	13	0.7	40.0	4.8	4.0
70	30	0.6	35.0	5.0	3.5

From these figures it appears that the break from a friable material to a plastic material, that is, the lower slope limit, occurs when more than 5 molecular layers of water have been added to the sample, regardless of the silt content. It should be noted that the rigidense values at this point are fairly constant. Grim and Cuthbert found that the water film thickness per unit cell of montmorillonite at minimum bulk density for a calcium montmorillonite clay was very close to 5 molecular layers (Grim, R. E., and Cuthbert, F. L., 1945). This observation is in good agreement with the data in Table III, column A. It should be mentioned here, however, that for silt only, the curve suggests that below 40 percent content the water is fixed

rigidly and holds the silt particles together rather firmly. Above 40 percent water content, the water molecules are rather abruptly disorganized and the curve thus becomes vertical. Very little, if any, water is absorbed thereafter. We cannot therefore make the simple assumption that silt absorbs a negligible amount of water, but rather it must be admitted that for a given surface area the silt particles are apparently able to hold small quantities of water more tenaciously than can clay.

The Rd. penetration curve indicates that a given volume of silt actually absorbs about 40 percent water before the bonding of the water molecules becomes so weak that random circulation results. If the silt fraction in the montmorillonite-silt mixtures is allowed for in this manner we find that the montmorillonite absorbs water according to Table III, column B. The values are rounded off to hundredths.

It may be seen that a mixture of 87 percent montmorillonite and 13 percent silt has essentially the same lower slope limit as silt alone. Smaller portions of silt shift the lower slope limit to the right, larger portions to the left. The conclusion suggested is that clay-silt mixtures, with silt varying between 15 and nearly 100 percent, are more unstable for low water content than where silt is less than 15 percent or where silt is 100 percent. It is suggested by field evidence that the foregoing statement holds true for silt, clay, or silt-clay mixtures in various stages of desiccation near their lower slope limit.

For all water contents beyond the lower slope limit (greater than about 45 percent water) it is clear that the amount of silt is inversely related to the stability of a sediment.

The stability of sand is greatly diminished by small additions of silt or clay.

The curves for montmorillonite and kaolinite are similar except for steepness of the sloping portion of the curve and the length of the sloping portion. The illite and halloysite used in these experiments showed no plasticity, but this is not necessarily the case with all mica clays and halloysites. The silt curve shows no plastic properties. The flatter the slope of the clay mixture curves, the more gradually are the water molecules disorganized by the additions of more water. That is, the more highly plastic materials probably retain more perfect orientation of the water molecules at high water contents than do the less plastic materials.

Sand and Rd.

The curve for sand was obtained from clean sand between 0.062 and 0.42 mm in diameter. At zero water content the penetrometer literally sprayed the grains of sand apart and sank to a depth of 2.8 centimeters. Upon adding 5 percent water to the sand the penetrometer sank only 1.0 centimeter, indicating that the water added to the sand formed films around the sand grains and increased the attraction of one grain for another. Additions of more water, up to about 30 percent, resulted in a fairly uniform increase in penetration up to 2.4. Beyond 30 percent water, further additions did not cause the penetrometer to sink any deeper. Most clean sands would probably have this same type of curve. The exact nature of the curves would depend on size distribution, skewness, roundness, shape, organic content, etc.

Some rigidense experiments on sieved and cleaned sand fractions were carried out. In one experiment Rd. was run on individual grade sizes based on the $\sqrt{2}$ Wentworth grade scale. The samples were saturated with water, packed thoroughly by bumping, and Rd. determined. The results are plotted in Figure 6, curve A. This experiment shows that Rd. increases with increase in grain size. This observation

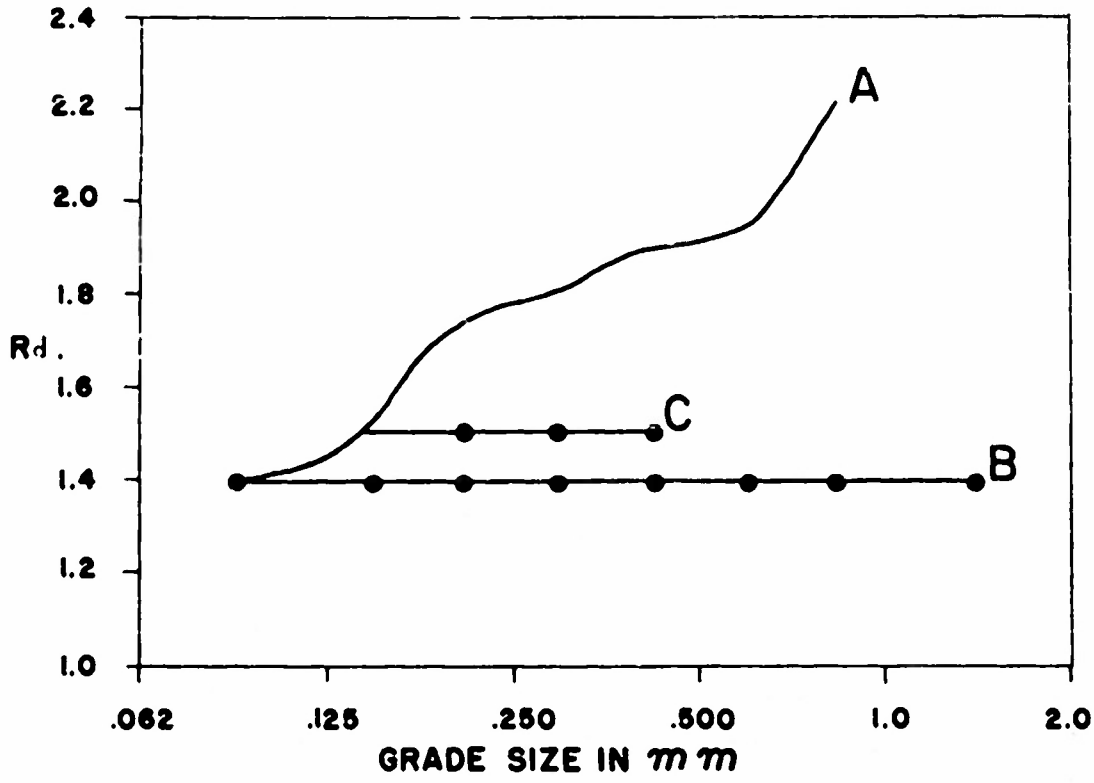

FIGURE 6
Relations between Rd. & Grade Size

A_ Rd. as a function of each grade size.
B_ Rd. as a function of mixtures of successively larger grade sizes with the grade size .062-125mm.
C_ Rd. as a function of mixtures of successively larger grade sizes with the grade size .125-.177mm.

is in agreement with the field observation that fine sand bottoms are harder and more compact than coarser sand bottoms. It is also interesting that longer cores have been secured from coarse sand bottoms than from fine sand bottoms. Traction zone thickness is greater in coarser sediments.

Sorting and Rd. in Sand

It was proposed further to determine the effect of sorting of sediments on Rd. values. To this end, the samples used in the above experiment were mixed in successive grades from the smallest to the largest. To samples of the smallest grade size (.062-.125), equal volumes of successively larger grade sizes were mixed. Rigi-dense was run after each successive mixing. The results are plotted in Figure 6, curve B. It appears from this curve that sorting is not a significant factor in determining Rd. values. When sediments are mixed in equal amounts the Rd. value will correspond to the smallest grade size present. To test this idea samples were mixed in the same manner, but using the grade size 0.125-0.177 mm as the lowest grade size. Again, the curve was flat, showing the dominant influence of the smallest grade size present (Figure 6, curve C).

The next step was to find out whether or not the smallest grade size is the influential factor in multimodal distributions. It has been found that the smallest grade size in a sediment sample whose volume is at least one-half of the volume of each of the larger grade sizes, determines the Rd. value as if it were the only grade size present. It does not seem to matter whether the sediment is unimodal or multimodal.

Skewness and Rd. in Sand

Since grain size is an important factor in determining Rd. and sorting is apparently not a significant factor, it follows that skewness is probably an important

feature of sediments insofar as their supporting capacity is concerned.

Samples were prepared with skewness varying from the coarser to the finer sand sizes. It was found that Rd. was affected by pronounced degrees of skewness.

Kurtosis and Rd. in Sand

Kurtosis is very definitely related to Rd. in that the less the peakedness of the distribution, the more nearly will Rd. conform to the smallest grade size present in the sample.

SUMMARY

Interpreting the data from the various experiments performed on sand allows us to make a preliminary statement regarding the Rd. value for these sediment samples. Rigidense is controlled by the smallest grade size whose weight reaches at least 50 percent of the weight of the largest grade size present in a sample. This knowledge is of considerable importance to soil mechanics.

The data is admittedly rather meager from a statistical point of view. More details of the relation between bearing capacity of sediments and grain size distribution could be found with further experiments. Relation of the mean grain size to Rd. should be studied, as well as refined experiments on skewness and kurtosis. Only the more obvious relations are reported in this report.

Only calcium saturated clays were used in the experiments reported on in this report. Sodium and other inorganic ions affect the plastic properties of sediments, and organic molecules in exchange positions may have particularly pronounced effects on plastic materials (Grim, R. E., et.al., 1947).

Sinking of a mine into underwater surface sediments depends on the cohesive and frictional properties of a sediment. A clean sand or gravel offers frictional resistance

to an imposed load, whereas a clay offers cohesive resistance. Most sediments fall between these two extremes.

The rigidense instrument is used to measure the combined cohesive and frictional properties of an unconsolidated sediment, and to study the plastic properties of such a sediment.

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