

# Principles of Soil Mechanics:

## V—Physical Differences Between Sand and Clay

Commonly Noted Differences in Behavior—Grain Size and a New Uniformity Diagram—Shape of Grains and Structure—How Shrinkage, Cohesion, Plasticity and Settlement Are Affected

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ON SUPERFICIAL examination sand and clay seem to be essentially different materials. Their salient differences are summed up as follows:

### DIFFERENCES BETWEEN SAND AND CLAY.

Clay	Sand
(1) Volume of voids may be as high as 98 per cent of the total volume.	(1) Volume of voids is about 50 per cent at the maximum.
(2) Shrinks in drying.	(2) Does not shrink in drying.
(3) Has a very marked cohesion, depending on the moisture content.	(3) Has negligible cohesion when clean.
(4) Is plastic.	(4) Is not plastic.
(5) Compresses very slowly when load is applied to the surface.	(5) Compresses almost immediately when load is applied to the surface.
(6) Is very compressible.	(6) Is far less compressible than clay.

Each of these properties represents the combined effect of several causes. Therefore, though the statements of the list are typical of what is found in current literature on soil mechanics, from a physical point of view they are no more satisfactory than, for example, the statement that two kinds of rock differ in brittleness, or two kinds of paraffin in tenacity and consistency. None but crude empirical conclusions can be drawn from such vague and general allegations, at the risk of confusing properties which physically may be altogether different. Atterberg, for example, confused the compressive strength of semi-solid clay with its resistance to penetration, and after assembling such heterogeneous data in a single diagram he was led to erroneous conclusions (see his "Konsistenz und Bindigkeit der Böden," *Internat. Mitteilungen für Bodenkunde*, 1912).

To characterize the properties of soils accurately we are obliged to trace these properties back to their physical sources. For the properties of clay this has been done in the preceding articles. It remains to analyze the properties of sand in similar manner and compare them with those of clay.

**Grain Size and Uniformity**—Considered as grain aggregates, clay and sand are characterized by their size of grain and uniformity. These factors are best expressed by a graphical representation of the results of mechanical analyses. The type of graph used should be such that the uniformity curves for materials of similar degree of uniformity will be of similar shape even though their fineness differs—the shape of the curve representing any material should be independent of the "effective size" of the grains. This can be accomplished by making the abscissas of the diagram proportionate to the logarithm of grain diameter. Thus, in Fig. 1,  $x = a \log d$ . Accordingly, a grain diameter  $d_2$  which is  $n$  times as large as a grain diameter  $d_1$  will be represented by a point at a fixed distance ( $a \log n$ ) to the right of the point  $d_1$ , regardless of the absolute values

of  $d_1$  and  $d_2$ . Such a diagram presents exceedingly instructive uniformity curves.

**Uniformity Curves**—Fig. 2 represents the mechanical analyses of nine different materials. Abscissas represent logarithms of grain diameter, and ordinates represent the total weight of the grains of diameter smaller than this value, in per cent of the weight of the total mass. Points corresponding to Hazen's *effective size* are located on a horizontal line having the ordinate 10 per cent. All curves representing materials with an equal *uniformity coefficient* (Hazen) have an equal

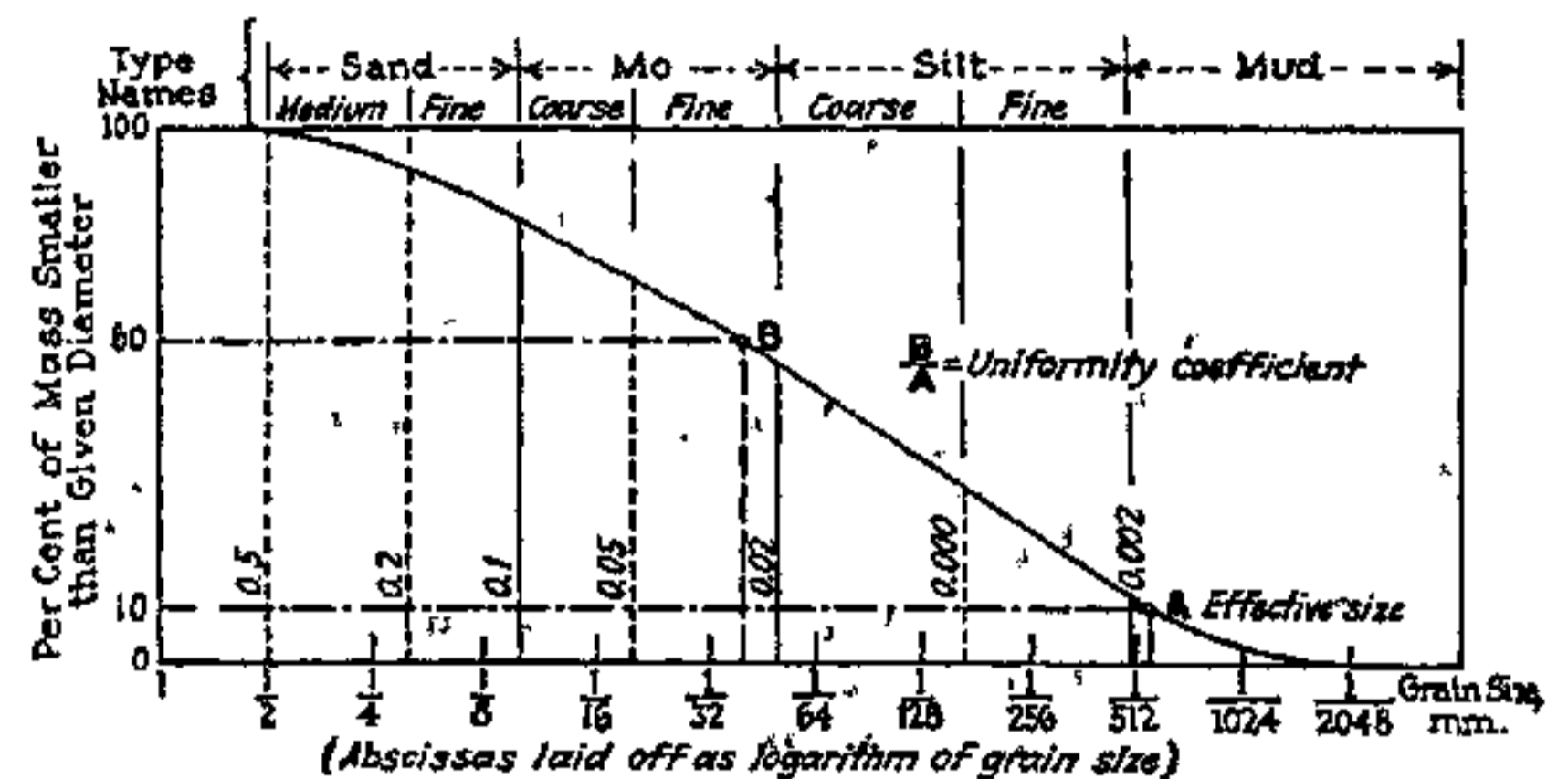


FIG. 1—METHOD OF REPRESENTING UNIFORMITY OF SOILS

(Form of curve is independent of fineness and depends only on uniformity.)

difference between the abscissas of their 10 per cent and 60 per cent points (see Fig. 1), regardless of whether the material is a coarse gravel or a colloidal powder.

The more uniform a material, the steeper is its uniformity curve. Hence two materials of different fineness but identical uniformity are represented in the diagram by curves of identical shape, and the fineness of the material (effective size) merely determines their position along the length of the diagram. Due to this property of the uniformity curves Fig. 2 reveals at a glance that in general *clays are far less uniform than are sands*. The loess from Virginia City represents an intermediate type in both uniformity and effective size.

The terms "mo," "silt" and "mud" used in the diagrams were originally proposed by Atterberg, and they seem to serve their purpose better than any other.

**Shape of Grains**—The grains of sand may be rounded or angular, with smooth or rough surfaces. Though these properties have a marked influence on internal friction, elasticity and permeability, yet all sands are alike (and differ from clay) in that their grains are bulky and rather rigid. Scalelike particles, as mica scales, represent only a minor accessory constituent. In contrast, clays are chiefly composed of flexible, scale-like particles. To be sure, the constituents of a "micro-mud" are so small that their shape can not be discerned even under a high-power microscope. Yet the assumption that clay particles are scale-like is sup-

ported by many proofs, of which a few may be mentioned.

A previous article described an apparatus called the interference contact indicator, consisting essentially of two glass strips enclosing a thin film of residual water. The film thickness, estimated by the Newtonian colors surrounding the water spots, amounts to about  $0.1\mu$ . In making several such contact couples I used (instead of distilled water) a very dilute suspension of mud, with particles of about  $2\mu$  size, and the water spots accordingly contained numerous clay particles of diameters 1 to  $2\mu$ . As the thickness of the films was not

unless its particles are smaller than about  $0.1\mu$ . However, clay particles of equivalent diameter as much as  $2\mu$  have, on account of their scale-like shape, as small a volume as the volume of bulky particles of diameter approximately  $0.1\mu$ . For this reason a clay whose largest grains have an equivalent diameter of  $2\mu$ , or  $0.002$  mm., possesses all the properties of a colloidal substance, and Atterberg was fully justified in calling all the clay particles below  $2\mu$  colloidal mud.

It is interesting also to recall that in examining colloidal powders produced by crushing and grinding various minerals, Atterberg found that only minerals

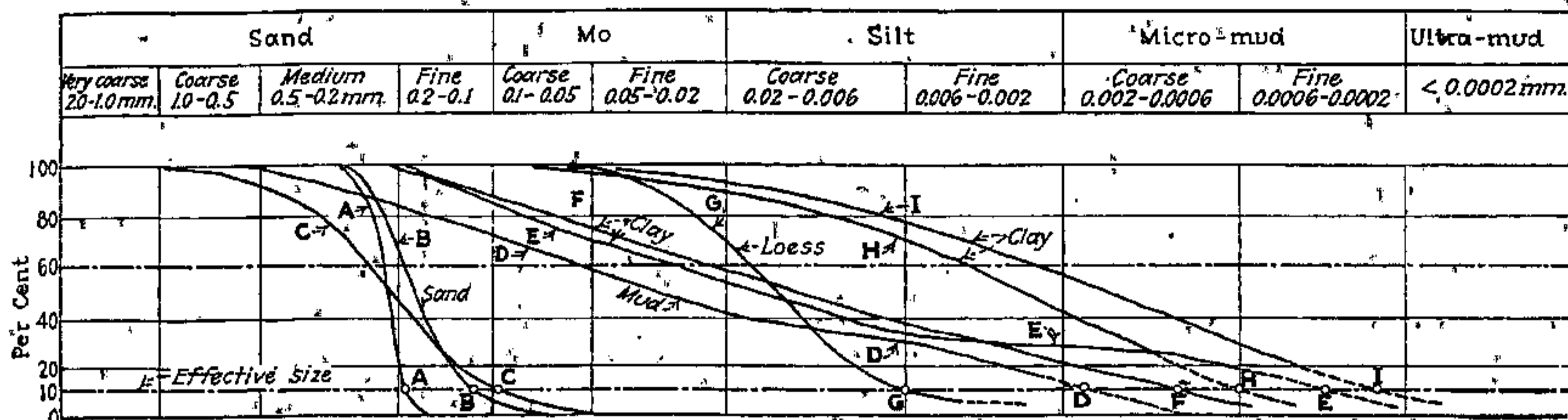


FIG. 2—NINE TYPICAL SOIL UNIFORMITY CURVES

- A—Coastal dune sand, Beklemé, Thrace.
- B—Beach sand, Rumeli Kawak, Thrace.
- C—Glacial sand, lower end of Ankogel Glacier, Austria.
- D—Mud, upper part of Golden Horn.
- E—Yellow residual clay, east shore of Bosphorus.
- F—Yellow marine clay, from earth slide in Thrace.
- G—Loess, Virginia City, Ill.
- H—Blue marine clay, from earth slide on Black Sea Coast, Thrace.
- I—Yellow marine clay, washed out of clay (F).

more than  $0.1\mu$ , the clay particles could not possibly be other than scale-like.

This direct evidence is strongly confirmed by indirect evidence drawn from permeability tests. The semi-empirical formula for the coefficient of permeability of clays (previously given) leads to the expression for the reduced coefficient of permeability,  $k_r = 1.9 d^2$  (cm./sec.), while the formula applicable to sand is  $k_r = (174 \text{ to } 100) d^3$ , in both of which  $d_w$  is the effective size. It thus appears that the coefficient of permeability of sand is 50 to 80 times greater than that of clay for the same effective size of grain. Both formulas refer to percolation at a standard temperature of 10 deg. C. through a material with a standard volume of voids of 50 per cent. In deriving the formula for clay it was further assumed that the water percolating through the clay has normal viscosity in spite of the small size of the voids. Hence the enormous difference between the formulas cannot be due to anything but a difference in the shape of the particles of the materials.

It is to be remembered that the term "diameter of a clay particle" by no means indicates the diameter of a globular grain of equal volume, but rather the diameter of a globular grain which sinks through the water at the same speed as the clay particle ("equivalent diameter"). As scale-like particles always sink with the flat side approximately horizontal, the volume of such a particle amounts to only a small fraction of the volume of a sphere of the same equivalent diameter. Therefore, even though sand be reduced to such fineness as to have the same equivalent grain diameter as a clay, yet a given volume of the sand would contain only a small fraction of the number of particles in an equal volume of clay, a fact which fully explains the difference between the two permeability formulas.

In chemistry a powder is not regarded as colloidal

of laminated or scaly structure furnish plastic mud; and all clays are plastic.

Sketch D in Fig. 3 shows a microscopic picture of the grains of coarse silt (0.02 to 0.006 mm.) extracted from a blue marine clay. A dilute suspension of this silt, examined under the microscope, was found to contain no colloidal particles at all. When the cover glass was shifted back and forth, numerous colloidal particles

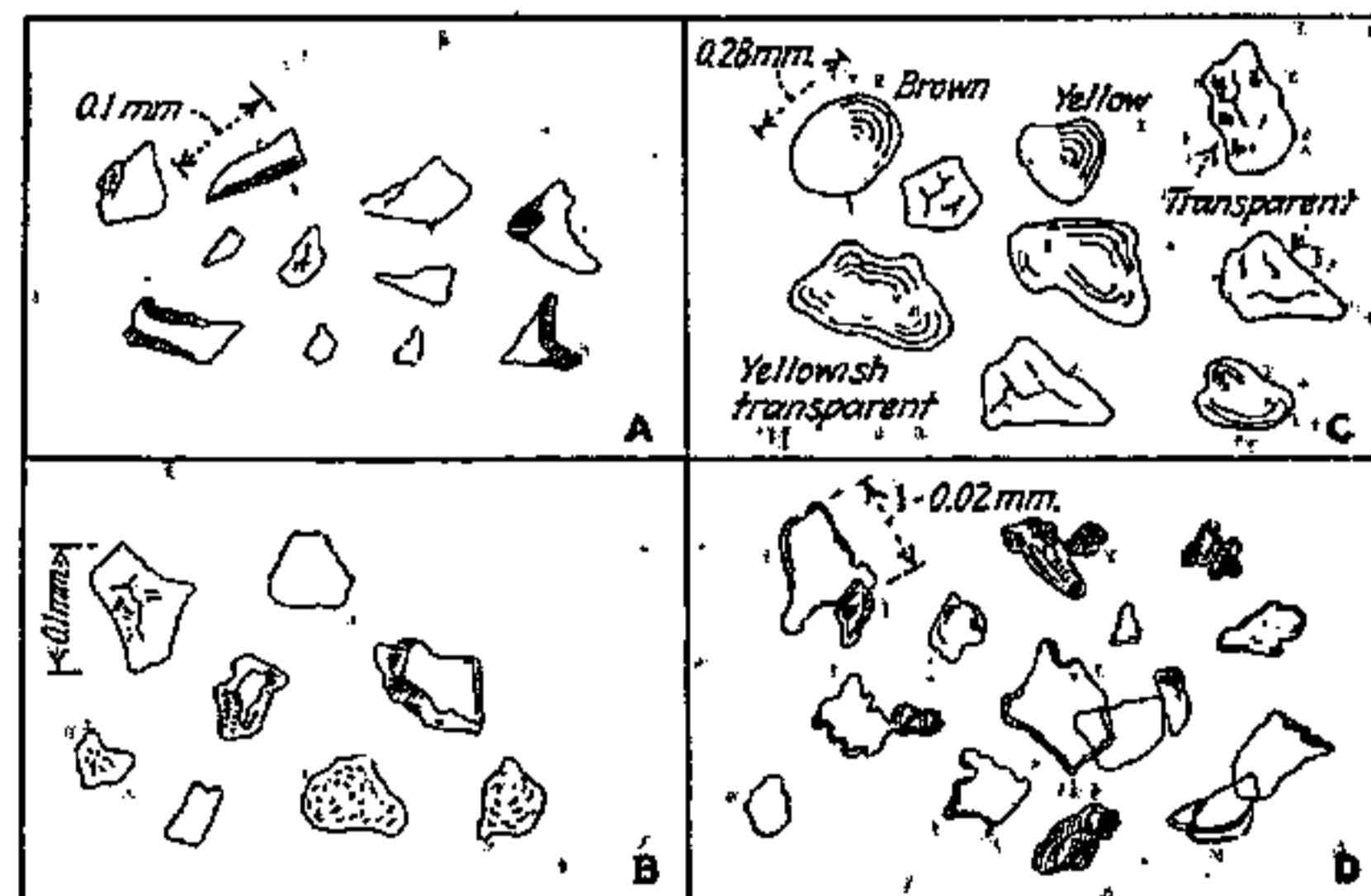


FIG. 3—CHARACTERISTIC SOIL PARTICLES (ENLARGED)  
A—Crushed quartz. C—Dune sand (A, Fig. 2).  
B—Glacial sand (C, Fig. 2). D—Coarse silt (from F, Fig. 2).

with a distinct Brownian movement appeared, showing how fragile are the scale-like particles. This fragility undoubtedly represents one reason why the uniformity curves of clays are so characteristically different from those of sands.

In conclusion it may be stated that throughout the author's studies no essential difference was found to exist between sands and clays other than the difference in grain size and shape. It will be shown, however,

that these two differences are fully adequate to explain the more obvious distinguishing features of the two materials.

**Loose and Dense Structure of Aggregate**—When a grain aggregate (sand or clay) in suspension is allowed to settle, sedimentation proceeds gradually, because the particles floating next to the bottom of the basin reach the bottom first. Suppose, now, that part of the sediment has been deposited, and a newly-arriving particle settles on its uneven surface, Fig. 4. Its movement, hitherto vertical, is disturbed by two new forces, the resistance of the sediment to penetration, and initial friction\* acting at the point of contact between particle and sediment. If the grain has the size of a sand grain, the initial friction is negligible compared with the weight of the grain. The weight and the reaction, then, form a couple which rolls the particle down to the bottom of the adjacent depression. The structure of the sediment thus formed will be loose (Fig. 5, upper right). By jarring the vessel the structure may be made dense (upper left). As there is practically no adhesion between the particles, the maximum volume of voids cannot be much larger than the corresponding volume of voids of a mass of equal spheres, i.e. 47.6 per cent, and in fact measurements show that the volume of voids of a cohesionless sand never exceeds about 50 per cent (void-ratio 1.0). On the other hand, if the arriving particles are very small the bond produced by initial friction may be stronger than the rolling tendency, so that the particles remain in the position of first contact, and the structure of the sediment becomes spongy (lower left in Fig. 5), with a maximum void-ratio (as found by measurements) of about 4.

Let us finally assume the particles to be of colloidal size. Such particles remain in suspension forever unless they are precipitated by adding a few drops of an electrolyte. Before the electrolyte was added the particles moved with a considerable speed through the liquid (Brownian movements) and repelled each other because of their electric charges. The electrolyte neutralizes the electric charges without eliminating the physical cause of the Brownian movements.

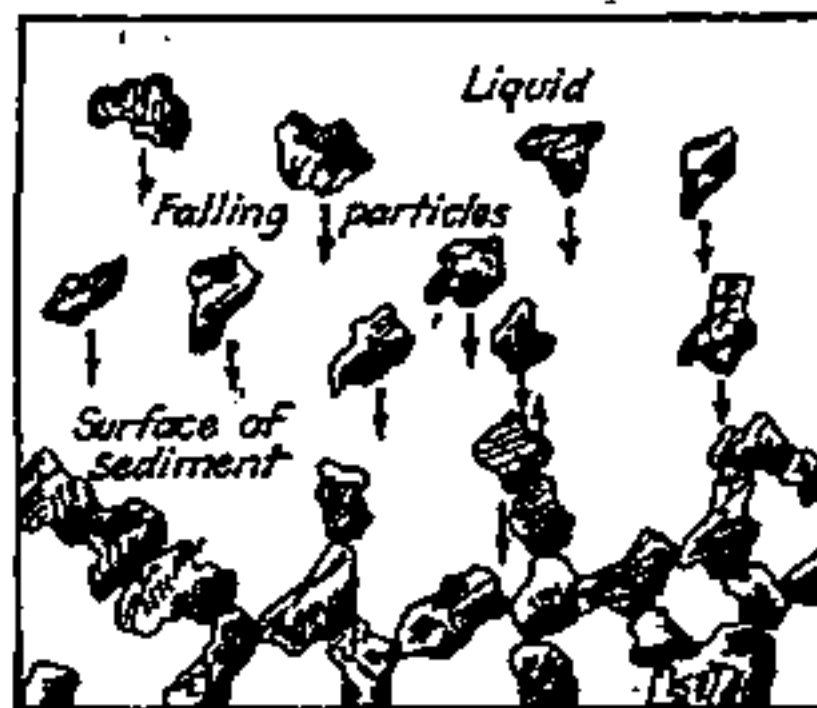


FIG. 4—SEDIMENTATION OF FINE POWDER

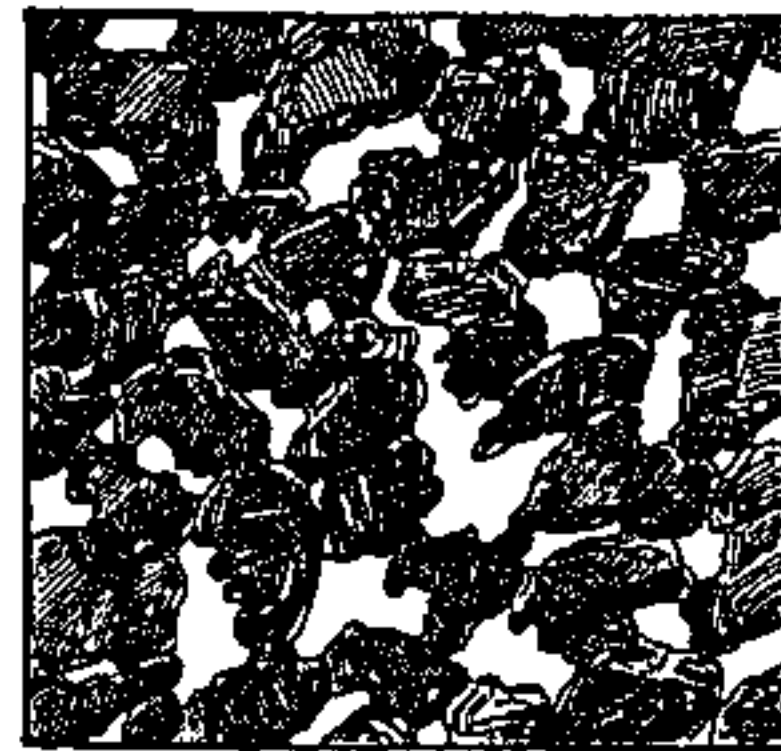
Hence the particles collide in the liquid, and as soon as two particles collide initial friction comes into action and the particles stick together. Thus spongy flocs are formed, which build up a spongy sediment similar to that just described, but with a floc in place of each grain. The resulting structure may be called a spongy structure of the second order (lower right, Fig. 5). Maximum void-ratio corresponding to a simple spongy structure being 4, the maximum void-ratio of this last type ought to be about 4<sup>2</sup>, or 16, corresponding to a volume of voids of 94 per cent.

Thus we can explain item (1) of the list of differences between sand and clay merely by the difference in grain size.

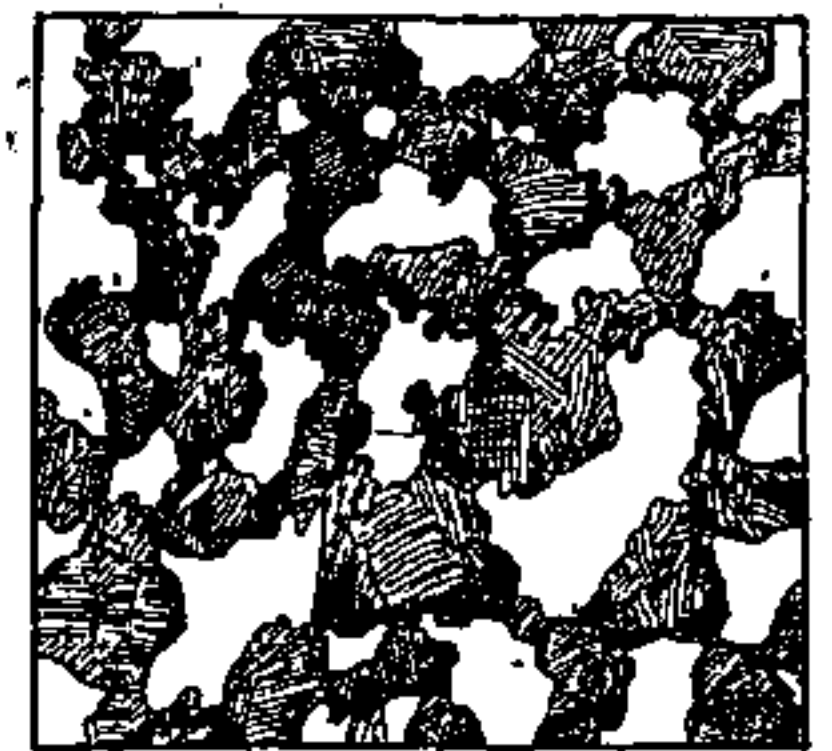
Sedimentation tests with powders of different fine-

\*The term initial friction as used by the author denotes the shearing strength of the clay when not under pressure, either external or capillary.

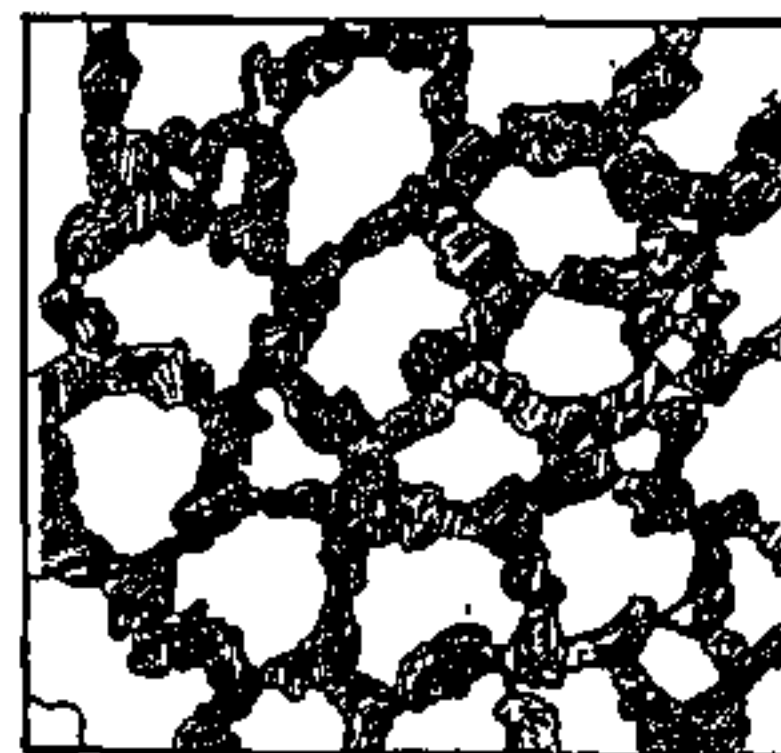
ness (extracted from mixed-grain aggregates by wet mechanical analysis) gave support to this explanation. As diagrammed in Fig. 6, fine powders even when thoroughly consolidated by jarring could not be reduced to



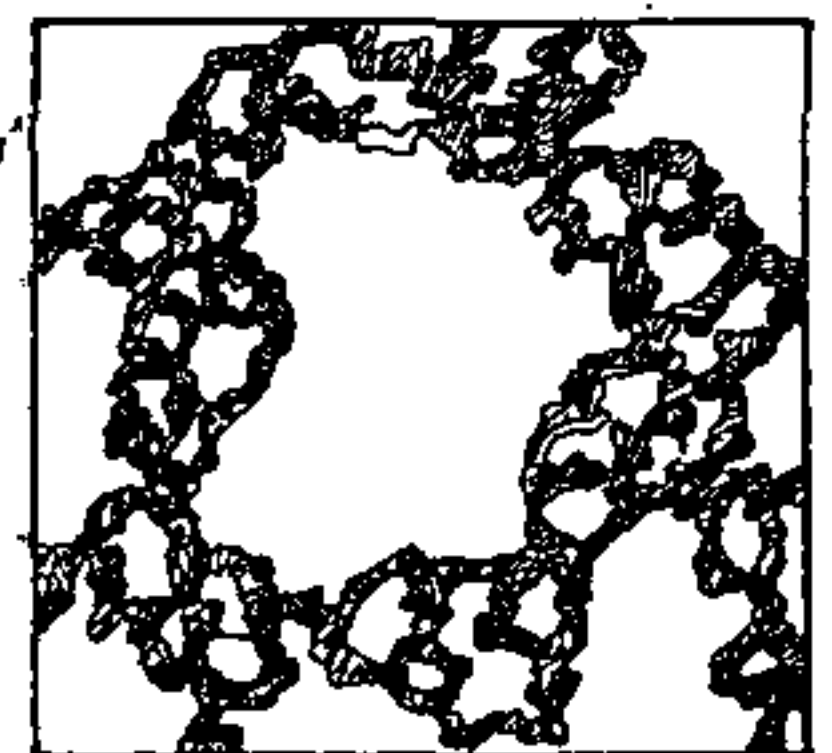
Dense Granular



Loose Granular



Spongy



Spongy of the second order

FIG. 5—MAIN STRUCTURE TYPES OF HOMOGENEOUS SOILS

the denseness of coarser sediments loosely deposited. This fact gives us an idea of what an important factor initial friction is, provided the number of points of contact per unit of volume of the sediment is very great. These sedimentation tests were made in test tubes 1.6 cm. in diameter. Slow sedimentation in wider vessels would undoubtedly lead to smaller values, yet the test results can be taken as confirming the explanation.

**Difference in Shrinkage**—If a piece of clay dries, it shrinks; the voids of the clay remain filled with water until the shrinkage limit is reached. In a previous article it was shown that the shrinkage represents the compression produced by the capillary pressure, and that the maximum intensity of the capillary pressure (transition pressure) depends on the grain size. In terms of the maximum height  $h$  in meters to which water can rise in the mass by capillarity, the transition pressure in kilograms per square centimeter is  $0.1h$ . For a very fine sand  $h$  is approximately 0.05m, hence the transition pressure would be 0.005 kg./cm.<sup>2</sup>, while fat clays have transition pressures of 200 kg./cm.<sup>2</sup> and more. A pressure of 0.005 kg. per cm.<sup>2</sup> cannot possibly produce any noticeable compression of the material. This fact accounts for item (2) of the list of differences between sands and clays.

**Cohesion**—Item (3) is also readily accounted for, since the maximum cohesive (shearing) strength of a grain aggregate is equal to the product of the transition pressure by the coefficient of internal friction of the material, so that sand cannot exhibit much cohesion.

**Plasticity**—A fact rather more difficult to understand is that colloidal quartz powders (microscopic sands) have no plasticity, while clays of equal fineness are very plastic. A body is plastic if its shape can be changed while its volume remains constant. To perceive the reason why microscopic sands are not plastic, the reader must refer back to the well-known sandbag experiment performed by O. Reynolds (*Phil. Mag.*, 1885). Rey-

nolds observed that a rubber bag full of dry sand opposes small resistance to change of shape, while if the bag is sealed after the voids of the sand are first filled with water it becomes as hard as stone and can be loaded heavily without changing shape. This fact is obviously due to the bulky shape of the sand grains; the arrangement of such grains cannot possibly change unless the grains roll over each other, and these grain movements are possible only when the structure temporarily becomes very loose, which would involve increase of the volume of voids. In a dry sand there is no obstacle to change of volume of voids, but when the voids are completely filled with water, and in addition air is prevented from entering, the volume of voids must remain constant; hence the grains cannot move and the content of the rubber bag makes the impression of being solid.

The nature of this phenomenon does not depend on grain size, provided the structure of the sand is not spongy but granular. A sediment consisting of a colloidal quartz powder is originally spongy and in this state is mobile, just the same as a spongy clay sediment;

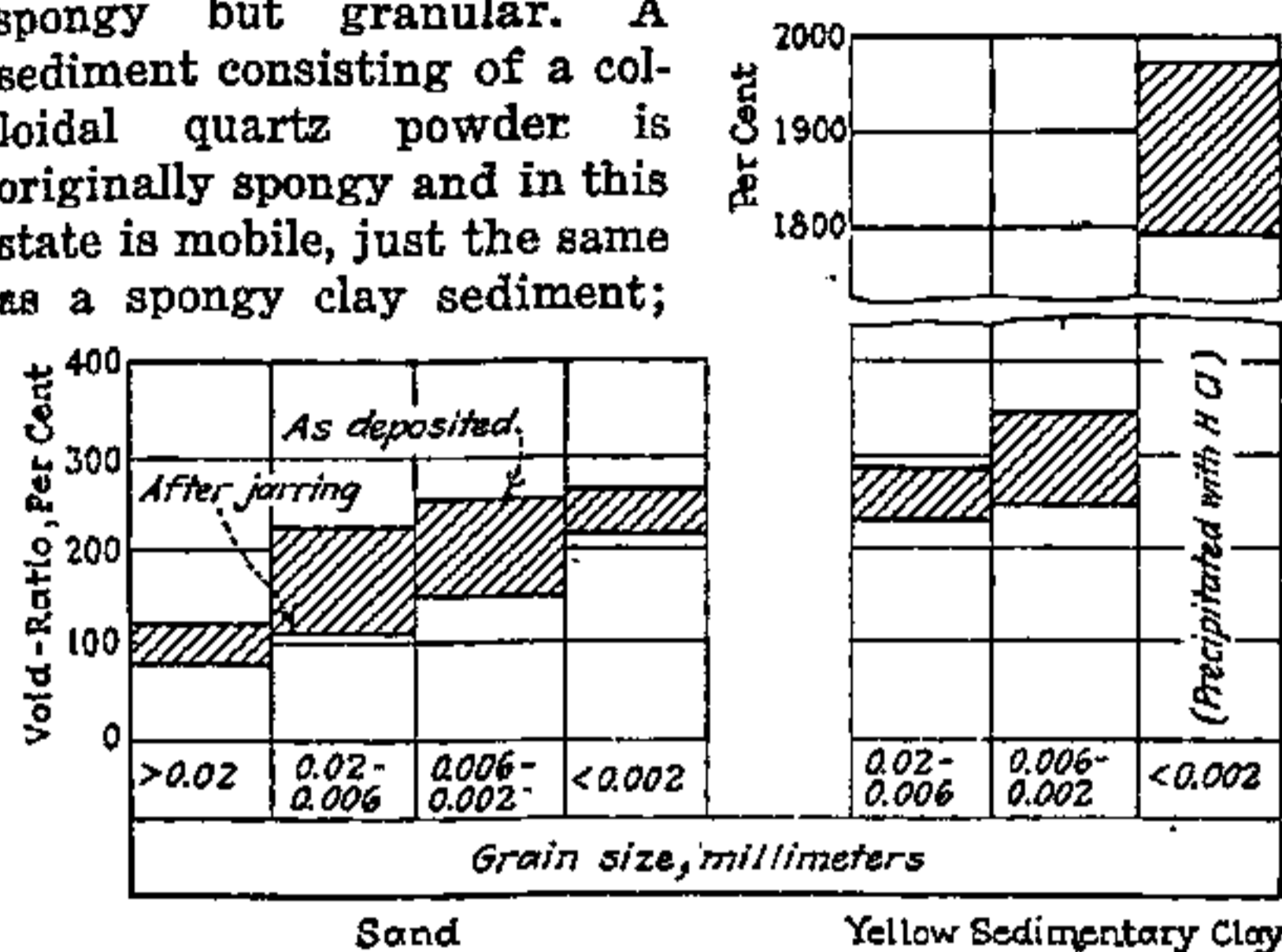


FIG. 6—VOID-RATIOS OF CLAY AND SAND SEDIMENTS

but when the capillary water of the quartz powder is allowed to evaporate, capillary pressure compresses it to granular structure. In this state, because of its bulky grains, it cannot change shape without changing volume, as shown by Reynolds' experiment. Hence neither sands nor colloidal powders with bulky grains are plastic.

In the case of clay, though held by the surface tension of the capillary water just as firmly as if enclosed in Reynolds' rubber bag, the particles are scale-like, and therefore can slide over each other while the volume of voids remains practically constant. Therefore clays are plastic. Item (4) of the differences between sands and clays is thus accounted for as the effect of size and shape of particles.

Naturally, as difference of grain size and form is one of degree, we may expect to find materials of various degrees of plasticity between the extremes of the non-

plastic and the highly plastic. The most suitable method for expressing the degree of plasticity is that proposed by Prof. A. Atterberg, as already explained. Table I contains a list of the characteristic limits for colloidal powders produced by crushing and grinding different minerals. The degree of fineness of all the powders used in the tests was approximately the same. The table shows clearly the intermediate stages between high plasticity (talc, biotite) and complete lack of plasticity (colloidal quartz powders). For powders derived from the same material, plasticity was found to increase with a decrease in average size of grains.

Settlement—Coming to item (5), we again find grain size and shape to furnish a complete explanation. Loading the horizontal surface of a water-soaked layer of sand produces almost instantaneous settlement because the excess water finds small resistance to its escape from the compressed material; but in clay the low permeability causes an enormous resistance to escape of the capillary water, and therefore settlement under load proceeds slowly.

TABLE I—PLASTICITY OF FINE MINERAL POWDERS  
 (Grains smaller than 0.002 mm. Figures from Atterberg's, "Die Plastizität und Bindigkeit der Tone," *Internat. Mitt. für Bodenkunde*, 1913. The tabulated figures are moisture content in per cent of weight of solid matter.)

Mineral	Lower Limit of Plastic State	Lower Limit of Liquid State	Coefficient of Plasticity (= Difference of Two Preceding Columns)
Biotite	44	87	43
Talcum	48	76	28
Chlorite	47	72	25
Kaolinite	43	63	20
Hematite	20	36	16
Limonite	27	36	9
Quartz	35	35	0