An historical perspective on the theory and practice of soil mechanical analysis

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ABSTRACT

In this paper the history of soil mechanical analysis is traced and evaluated to place our current concepts in perspective, from both a research and teaching viewpoint. The early period of research in mechanical analysis (from 1880 to 1920) is characterized by laborious separation techniques such as decantation and elutriation, which were replaced in the 1920s by the modern pipette and hydrometer methods. The pipette method is based on Stokes' Law and has become the standard method, whereas the Bouyoucos hydrometer method is empirical and its popularity is based on simplicity and speed of use at the expense of accuracy. Revised hydrometer methods based on Stokes' Law improve its accuracy, but continued use in research and instruction of the 2-h hydrometer reading tends to promulgate an approximation as a method of choice. Alternatives to the Bouyoucos method for use in soils teaching laboratories are discussed.

Additional Index Words: Particle size analysis, Hydrometer, Pipette method, Bouyoucos, Stokes' Law, Sedimentation.

The study of the origins of scientific concepts is an interesting and ultimately useful endeavor from several points of view. For the research scientist, the historical background of a pertinent study area forms the basis of the current set of hypotheses and experimental approaches. For those involved in teaching, an historical perspective can be a valuable teaching tool to stimulate student interest by introducing the personalities and debates that molded our current ideas about a particular topic. In both cases, the history of a concept often teaches (or reminds) us that the process of science, research, is often precisely that: re-searching for explanations, methods, and applications that have been studied many times before. An awareness of the process of science as the refinement of concepts over time, the replacement of one hypothesis by another, is a valuable lesson: “re-searching” will render out students’ textbooks obsolete during their lifetimes, and hence the ability to continually evaluate and apply new hypotheses may become as important to our students as familiarity with a “static” body of current concepts.

The study of soil is relatively young as a science, yet our roughly 100-yr history offers many examples of this scientific process, perspective to our current knowledge and illustrating the development of modern concepts. Most introductory texts describe at least briefly the search for the “principle of vegetation” during the 18th and 19th centuries (Russell, 1973 gives a more complete account), and the advances in soil genesis and classification made by the Russians in the 1880s. Use of these historical scenarios in either an anecdotal or problem-solving approach can be effective in adding interest and diversity during lectures.

An important aspect of soil science commonly discussed in many soil courses is particle-size distribution and its determination by mechanical analysis, another topic with a long but less well-known history. We mention Stokes and Bouyoucos in our lectures, and describe the pipette and hydrometer techniques, perhaps with little feeling for how these people and others arrive at their conclusions and what these techniques mean to us today. Our interest in this topic was spurred by an inconsistency discovered in class between two methods of mechanical analysis, which resulted in a thorough review of the historical literature on the theory and methodology of particle-size analysis. Our goal began as a simple clarification...
tional resistance of a body moving through a viscous medium as water. His major contribution was to describe the frictional resistance of a body moving through a viscous medium as a function of the radius (r) and velocity (v) of the body and of the viscosity of the medium (η):

\[ F_r = 6\eta rv \]  

where \( F_r \) is the frictional force acting to slow the acceleration of the body. Another decelerating force is the buoyant force (\( F_b \)), equivalent to the weight of medium (liquid) displaced by the body and computed as the mass of medium displaced (or the product of its volume, \( 4\pi r^3/3 \), and density, \( \rho_2 \)) times the gravitational constant, g:

\[ F_b = (4\pi r^3/3)\rho_2 g \]  

These two forces are countered by the gravitational force (\( F_g \)) that acts to accelerate the body, given by the product of mass (or volume times particle density, \( \rho_2 \)) and g:

\[ F_g = (4\pi r^3/3)\rho_2 g \]  

As a particle begins to fall through a liquid medium, it rapidly accelerates, as \( F_r \) is small due to the low velocity, and \( F_g > F_b \) due to the differential densities of particle and liquid. As velocity increases, frictional forces increase, and the particle reaches terminal (constant) velocity when opposing forces balance, that is

\[ F_b + F_r = F_g \]  

Substituting Eq. [1], [2], and [3], into Eq. [4], cancelling terms, and solving for v, particle velocity, gives the familiar form of Stokes' Law:

\[ v = (2/9)(r^2g/\eta)(\rho_2 - \rho_1) \]  

At fixed temperature \( T \), \( n \) and \( \rho_1 \) are constant, and with a given \( \rho_2 \), the constants in Eq. [4] may be collected to yield:

\[ v = kr^2 \]  

with k (combined constant) = 8946 at \( T = 20^\circ C \) and \( \rho_2 = 2.65 \text{ Mg m}^{-3} \), with units of \( V \text{ in cm s}^{-1} \) (Jackson, 1972).

This simple exponential relationship is the basis of the mechanical separation of particles during particle-size analysis. The derivation of this equation from fundamental physical principles as shown above is not difficult to present to students and demonstrates the application of basic physics to soil analysis. It is interesting to note that this law has been used in studying the rate of fall of water drops during cloud formation, in determining electronic charge by Millikan in his "oil drop" experiments, and in determining the viscosity of liquids, as well as other physical chemistry applications—including mechanical analysis.

METHODS OF MECHANICAL ANALYSIS

Early Research

It is interesting to ask students precisely how, given Stokes' Law, they might actually measure particle size distribution. Their answers might reflect the attempts of soil scientists in the period 1870 to 1920 to devise simple methods of utilizing Stoke's Law. Sieving is, of course, useful only on larger particles: the finer fractions of soil were recognized early to be far too small to be retained on any seive. Sedimentation in water was used as early as 1708 by Houghton to quantitatively separate the "earth" fraction from sand, and scientists of the late 19th century also seemed to have used sedimentation empirically, without specific knowledge of Stokes' Law (Keen, 1931). Hilgard (1892) developed an elutriator that used the velocity of flowing water to wash progressively coarser particles from a sample in a column apparatus, using a microscope to determine the sizes of particles in different fractions. Osborne (1887) and workers in Germany also used microscopic measurement to determine particle sizes of soil separated by decantation after arbitrarily chosen settling times, using sizes of 1 to 0.05 mm diam. as sand, 0.05 to 0.01 mm diam. as silt, and <0.01 mm diam. (later, <0.005 mm diam.) as "dust" or clay. Hall (1904) may have been one of the first to utilize Stokes' Law in the decantation method, correctly calculating times of sedimentation for a range of particle sizes down to <2 μm, which he referred to as the "clay" or colloid fraction. Oden (1915) in Sweden also rigorously applied Stokes' Law to soil mechanical analysis, in the process developing the "sediment balance," an ingenious devise that used a balance pan suspended in the sedimenting solution and continuously recorded the weight of sediment accumulated on the pan. Complete particle-size distribution curves were obtained in this way, with sizes down to submicrometer range as computed by Stokes' Law. Unfortunately, serious errors due to convection currents under the balance pan were discovered (Keen, 1931), and the benefits of the laboriously collected complete distribution curves, as opposed to a few discrete fractions, were also questioned.

Both the elutriation and decantation methods were also time-consuming, requiring complete separation of particle-size classes. To complete the separation by decan-
tation, 6 to 10 d were required for a set of eight samples, with large volumes of particle suspensions to be evaporated (Osborne, 1887).

The Pipette Method

By 1920, accelerated soil survey work and soil fertility investigations were demanding more rapid methods of mechanical analysis. In 1922 the pipette method was developed in its modern form by Robinson (1922) and simultaneously by Jennings et al. (1922) and Krauss in Germany, using somewhat different sampling techniques. Robinson's method was based on settling velocities as in the decantation methods, but rather than attempting to collect and weigh entire size fractions, the pipette was used to sample only a portion of the fraction at a depth calculated to be free of all particles greater than a specified size (Fig. 1). With many samplings, complete distribution curves could be constructed, or a few points used to define discrete classes. Long sedimentation times (up to 24 h) were used for clay determinations (apparently using a 1-μm upper limit), but the ability to complete 20 or more analyses daily was a major improvement over older methods.

Bouyoucos and the Hydrometer

Also during the early 1920s, George Bouyoucos had been studying soil particle size. He developed a method, using heat of wetting measurements, to estimate soil "colloid" content, thought at that time to represent a very fine, highly reactive soil fraction. This approach, along with water adsorption techniques, gave estimates of colloid content agreeing with base (cation) exchange data, but were soon acknowledged to depend on the kind of colloid present, even though the identity of clay minerals would not be discovered until the 1930s. Sedimentation seemed to be the way to quantify the actual content of particle-size classes. In 1927 Bouyoucos adapted a milk density hydrometer to measure concentrations of clay suspended in a sedimentation cylinder (Bouyoucos, 1927; Fig. 1). He calibrated the stem of the hydrometer using known clay suspensions and found good agreement between hydrometer readings taken after 15 min sedimentation and colloid content by heat of wetting, although both sets of values appear to be high (Bouyoucos, 1928a). By this time a special hydrometer had been developed and marketed, along with the baffled cup and mixer for sample dispersion.

In 1928 Bouyoucos first applied Stokes' Law to the hydrometer method, but unfortunately used an incorrect formula and the wrong settling depth (by assuming the hydrometer measured an average density throughout the cylinder). He rationalized the long calculated settling times for clay (4 h for <5 μm particles) and "colloids" (24 h for <2 μm particles) compared to his 15 min reading by supposing that "colloid material may vary tremendously in size of particles," and further, that "any name may be given (to various size classes) that one desires" (Bouyoucos, 1928b). Such an attitude is partially a result of contemporary confusion over the definition of clay and colloids, but is also a realization that his method did not agree with theory. This led to the oft-invoked "compensating factors in the hydrometer method which tend to give the true final result and which the mathematical calculations do not take into account" (Bouyoucos, 1928b).

Comparison of Pipette and Hydrometer Methods

With the growing popularity of the hydrometer method due to its acclaimed rapidity and ease of operation, Bouyoucos attempted to place his method on a more solid footing by comparing it with the pipette method, which had been adopted in 1930 as the standard method for mechanical analysis by the International Society of Soil Science. Using a 1-h sedimentation time for <5 μm clay and 2 h for <2 μm colloids, he found the hydrometer values agreed "very well" with the pipette determinations, explaining the slightly finer textures given by the hydrometer as most likely due to dispersion problems (Bouyoucos, 1932). He rebuts those criticising his method as not following "certain physical laws" by presenting data showing poor interlaboratory agreement of pipette method data, even though the hydrometer was not similarly tested to ascertain its precision. Despite his acknowledgment that the hydrometer "may not be so accurate" in the fine clay (<2 μm) measurement, one senses his determination to defend the hydrometer in the apparent conflict with proponents of the pipette (Bouyoucos, 1932).

Twenty years later Bouyoucos published a "recalibration" of the hydrometer method, essentially another comparison with pipette data on a group of 17 soils (Bouyoucos, 1951). This study, still cited in current research literature and laboratory manuals, re-affirms the agreement of the two methods using the new particle-size definition of clay as <2 μm, changed from 5 μm in 1938. A close examination of the data shows that the 2-h hydrometer reading used for clay determination overestimates clay content by 5 to 10% on half the soils, particularly those high in silt. In their review paper,
Kilmer and Alexander (1949) also noted the "considerable margin of error" inherent in the hydrometer data; yet, like Bouyoucos, they attributed this to pretreatment or dispersion differences, despite their own statements that adequate dispersion is obtained with either overnight shaking or mechanical mixing, using common alkaline dispersing agents.

Our comparisons of the hydrometer and pipette on a selection of well-dispersed (overnight shaking in alkaline metaphosphate) southeastern topsoils (Table 1) demonstrate the overestimation of clay and underestimation of silt that is typical of hydrometer data compared to the pipette data. In the soils examined here, the apparent determination of silt as clay by the hydrometer resulted in textural class differences in three of the six soils studied.

The error in the hydrometer settling times is easily seen from a plot of sedimentation time for a given depth (computed from particle velocities using Eq. [6] vs. equivalent diameter, computed using Stokes' Law (Fig. 2). The velocity of particle settling depends inversely on the square of the particle radius, which causes velocity to decrease (or settling times to increase) dramatically for particles smaller than approximately 5 \( \mu \text{m} \). One- or two-hour settling times are reasonable approximations of settling times for 4- to 5-\( \mu \text{m} \) particles, but the 2-\( \mu \text{m} \) size obviously requires much longer times. Bouyoucos' 2-h reading really measures 4- to 5-\( \mu \text{m} \) particles; in soils with appreciable contents of 2- to 5-\( \mu \text{m} \) material, a 2-h reading will significantly overestimate "clay" content, even with a perfectly dispersed soil suspension. This is obviously the explanation for the data in Table 1.

Paul Day finally put the hydrometer method on a firm physical footing by showing the "effective depth" at which the hydrometer measures suspension density, amending Casagrande's earlier theoretical work with the hydrometer done in Germany in the 1930s (Day, 1950). This work confirmed the agreement of hydrometer readings with pipette determinations when Stokes' Law was used with the correct settling depth (Day, 1953) and led to recommendations of 10- to 12-h settling times for <2-\( \mu \text{m} \) sizes, which were adopted by the Soil Science Society of America and the American Society for Testing Materials (Day, 1956).

**IMPLICATIONS AND CONCLUSIONS**

The salient points of the saga recounted above might be summarized as follows: soil scientist struggled through a 40-yr period from 1880 to 1920 to find a rapid, standardized method of mechanical analysis, at the end of which time two "competing" approaches emerged—the pipette and hydrometer methods. Robinson's pipette method, rigorously based on Stokes' Law and elegantly simple, has come down to us 65 yr later practically unchanged, to become the standard method. Bouyoucos' adaptation of a milk hydrometer to measure suspended particles was ingenious, but his approach was purely empirical, and he consistently rationalized away apparent errors and inconsistencies. His publications dwell on the simplicity and speed of the method, and tend to blatantly advertise equipment associated with the method, from which he derived considerable financial gain. Yet the stature of George Bouyoucos was such that little direct criticism was leveled at the 2-h hydrometer method. Only recently has a review of this methodology (Gee and Bauder, 1986) categorically stated the errors involved, rather than simply ignoring the method altogether, which may amount to a tacit endorsement by omission.

The implications for our research and teaching in a narrow sense are obvious. The 2-h Bouyoucos method has too great an error potential even for routine soil characterization, as overestimation of clay content may result in placing soils in incorrect textural classes. The longer settling times required for either pipette analysis or the Day modification of the hydrometer (Gee and Bauder, 1986) categorically stated the errors involved, rather than simply ignoring the method altogether, which may amount to a tacit endorsement by omission.

**Table 1. Comparison of particle sizes of selected southeastern topsoils performed by the Bouyoucos hydrometer and pipette methods.**

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<th>Textural class</th>
<th>Sand</th>
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<th>Textural class</th>
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† 40 s and 2 h hydrometer readings (Bouyoucos, 1951).
‡ Sand sieved at 53 \( \mu \text{m} \); pipette samples at 10 cm (Gee and Bauder, 1986).
§ cl = clay loam; scl = sandy clay loam; sl = sandy loam; sil = silt loam.

![Fig. 2. Settling times for particles <10 \( \mu \text{m} \) in diam. through depths of 10 cm (for pipette method) and 17 cm (typical for hydrometer method), calculated from Stokes' Law at 20°C and with \( \theta _{f} = 2.65 \). Indicated points show 5 \( \mu \text{m} \) size cutoff after 2 h with hydrometer method and 2 \( \mu \text{m} \) size after 8 h using pipette method.](image-url)
are fully justified by the greater accuracy of these methods. In the introductory soils laboratory, the 2-h settling time is widely used (e.g., Foth et al., 1982) and may be retained by some as an admitted “approximation,” with the caveat that Stokes’ Law would demand much longer times if greater accuracy is desired. Or, if the number of students and available equipment allows, suspensions can be stirred sufficiently beforehand or allowed to settle after the lab period so that clay readings can be taken after adequate settling times (note in Fig. 2 that the asymptotic nature of the curve means that longer settling times, even up to 24 h, have much less associated error than too short a time). A micropipette method is also available (Miller and Miller, 1987) using a roughly 2-h settling time and a 2.5-cm sampling depth, but this method requires some skill in pipetting and analytical weighing capabilities as well.

In a wider sense, the history of mechanical analysis illustrates the progressive refinements of concepts and methods that epitomize the process of science. But it also provides a warning, particularly to those involved in instruction: By perpetuating simplistic and unverified ideas, we circumvent science and pass on to another generation the misconceptions we ourselves learned, but failed to rectify.

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