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A History of Particle-Size Limits

by

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INTRODUCTION

Soils consist largely of mineral particles in a wide range of sizes. It is advantageous to assign names, such as "sand", etc., to describe particles which lie between certain size limits. These names are convenient to use and give more information than merely stating that the particles fit certain size limitations.

Many systems of particle-size limits have been proposed and used, and have many discrepancies. For example, depending on the system used, a term such as "sand" may designate very different materials.

Since no clear-cut divisions can be made between members of a continuous series all particle-size limit schemes are arbitrary. The originators of the various systems were influenced by many factors: convenience of investigation, methods and equipment available for analysis, ease of presenting data, convenience for statistical analysis, previous work, and systems in use. The complications were further compounded because of widely varying fields of endeavor with varying background, outlook, and goals. For example, many inconsistencies are found in engineering depending on whether the size limits are used to differentiate soils, or characterize aggregates for concrete.

Some of the investigators have tried to place limits to correspond with the various properties of the soil components; others were more interested in the ease and convenience of obtaining and presenting data.

The purpose of this paper is to review many of the systems which have been proposed and used, and if possible, to suggest what may have been the reasons for the selection of the particle-size limits.

For ease in reporting and for better continuity, the remainder of this paper has been separated into three parts according to the source of information, i.e., agricultural, engineering, or geological literature.

SYSTEMS REPORTED IN AGRICULTURAL LITERATURE

Much of the early work in defining particle size limits for the various soil fractions was done by Germans. Among the early German systems was one given by Wanschaffe in 1814 (8). He used the following limits:

	Size, mm
fine gravel	> 2
very coarse sand	2-1
coarse sand	1-0.5
medium sand	0.5-0.2
fine sand	0.2-0.1
very fine sand	0.1-0.05
silt	0.05-0.01
fine clayey portion	< 0.01

Wolf (54) used:

	Sieve
stone	3-2 mm
coarse gravel	2-1 mm
fine gravel	1 mm-NO. 50 (0.35-0.39 mm)
coarse sand	No. 50-No. 100 (0.14-0.17 mm)
fine sand	No. 100-No. 16 (0.09 mm)
silt	< 0.09 mm

Kuhn (14) proposed:

	Size, mm
stone	> 5
coarse gravel	5-3

fine gravel	3-2
very coarse sand	2-1
coarse sand	1-0.5
fine sand	0.5-0.25
very fine sand	< 0.25

and a permanent committee for soil investigation (14) proposed:

	Size, mm
stone, gravel	> 5
fine gravel	5-2
very coarse sand	2-1
coarse sand	1-0.5
medium sand	0.5-0.2
fine sand	< 0.2

These systems were probably based on arbitrary selections of particle size limits.

In 1895 Williams, of Russia, presented the system used by A. Fadejeff in his lectures at the Agricultural Academic Petroffskaja (53). His classification was based on grain size and shape:

	Size, mm	Group
stones & pebbles	> 10	stony
coarse gravel & grits	10-7	gravelly
medium gravel and grits	7-5	
fine gravel & grits	5-3	
coarse sand	3-1	sandy
medium sand	1-0.5	
fine sand	0.5-0.25	

dust	0.25-0.01	earthy
coarse silt	0.01-0.005	
medium silt	0.005-0.0015	
fine silt	< 0.0015	

Williams agreed with this system except for the last group. He expressed the earth soil group in the following manner:

	Size, mm
coarse silt	0.25-0.01
medium silt	0.01-0.005
fine silt	0.005-0.0015
clay	< 0.0015

He called the last fraction clay because the soil owes almost all of its cohesion to this portion, the cohesion of the silts being due to organic matter. In addition, the specific gravity of the clay fraction is less than that of the other fractions. The transition from sand to silt results in a sudden strong increase in water retention, but the increase is even more significant when going from silt to clay. The same trend is observed with permeability; sand is very permeable, silt much less so, and clay sometimes is completely impermeable. The amount and rise of capillary water is also a factor. All of the larger particles are products of physical reduction of quartz and other minerals, while clay is a product of chemical weathering.

One of the early investigators in the United States was Hilgard (23, 24, 25), who used an elutriating device to perform mechanical analyses. His particle size limits show this influence:

	Size, mm	Hydraulic value, mm/sec
coarse grits	1-3	?
fine grits	0.5-1	?
coarse sand	(80-90) x 1/180	64
medium sand	(50-55) "	32
fine sand	(25-30) "	16
finest sand	(20-22) "	8
dust	(12-14) "	4
coarsest silt	(8- 9) "	2
coarse silt	(6- 7) "	1
medium silt	(4- 5) "	0.5
fine silt	(2.5- 3) "	0.25
finest silt	(0.1-2.0)"	0.25
clay	?	0.25

The values for particle size refer to the diameters of the largest and most nearly rounded quartz grains in each sediment, the quartz grains being used as standard. Hilgard felt his hydraulic values gave a better definition, representing the velocity of an upward current of water, in mm/sec, which will carry off a fraction of the soil, i.e., the lifting power of an upward current of water moving under a constant and uniform velocity. With respect to the porosity of the soil on the one hand and its compactness and resistance to tillage on the other, he felt silt sediment with hydraulic value of 0.5 mm (1/36 mm diameter) was neutral. Therefore, portions > 1/36 were designated as coarse materials which increase the lightness and porosity of soil in proportion to percentage. The fine portion, < 1/36 mm, modifies the plastic properties of the clay but also makes soil heavier in tillage than if it were absent.

In 1887 Osborne, of the Connecticut Agricultural Experiment Station (34), reported the results of a study of various mechanical analysis methods. He used purely arbitrary particle size limits which could be conveniently determined with his optical micrometer. Sieves of 1, 0.5 and 0.25 mm were used, and elutriation and sedimentation used for smaller particles. He designated:

	size, mm
sand	0.25-0.05
silt	0.05-0.01
dust and clay	< 0.01

Other limits used in his study for more detailed analyses were 1, 1-0.5, 0.5-0.25, 0.05-0.02, 0.02-0.01, 0.01-0.005, and < 0.005 mm.

Early workers in the U. S. Department of Agriculture adopted most of Osborne's limits (16, 17, 31, 52). Whitney used the following:

	size, mm
fine gravel	2-1
coarse sand	1-0.5
medium sand	0.5-0.25
fine sand	0.25-0.10
very fine sand	0.10-0.05
silt	0.05-0.01
fine silt	0.01-0.005
clay	0.005-0.001

He placed a lower limit of 0.001 mm for clay because a soil suspension which has stood for several weeks will show particles of that size. He evaporated a drop of the suspension on a cover glass, ignited and stained it, and studied it with an oil immersion microscope. Later the Bureau of Soils combined the two silt groups into one from 0.05-0.005 mm and designated clay as anything < 0.005 mm (16).

In 1899, Hopkins, of the USDA Bureau of Chemistry (28) made a proposal for a more scientific separation of soil particle sizes. To illustrate the arbitrariness of the method being used by the Bureau of soils he quoted correspondence from Osborne: "In working out the beaker method of soil analysis I employed the limits of the various grades with reference simply to convenience in using my eyepiece micrometer. I have always thought that the limits of the various grades should be determined by a careful consideration of the various conditions involved in the problem of proper mechanical analysis of a soil, and have been surprised to see that the arbitrarily chosen limits of the various grades employed by me have been followed by others in applying the method in practice."

Hopkins considered as a serious objection the fact that the ratios of the largest to the smallest particles of each division were not constant.

Div. No.	Size, mm	Ratio of diameters	Ratio of surfaces	Ratio of volumes	Theoretical % composition
1	> 1	-	-	-	12.50
2	1 -0.5	2	4	8	9.68
3	0.5-0.25	2	4	8	9.68
4	0.25-0.10	2.5	6.25	15.6	12.10
5	0.10-0.05	2	4	8	9.68
6	0.05-0.01	5	25	125	24.20
7	0.01-0.005	2	4	8	9.68
8	< 0.005	-	-	-	12.50

The theoretical percentages are based on a soil of uniform gradation.

The limits for divisions No. 6 are 2 1/2 times wider than for Nos. 1, 2, 5 and 7 and twice that of No. 4. In practical work a larger percentage falls in division 6 than in 5 or 7 because of the wider limits, not because of any peculiarity of the soil.

The differences in the ratios of surfaces and volumes are seen to be even larger, yet capillarity and porosity are more closely related to these than to the diameters.

Hopkins devised the following method, assuming a theoretical composition of a soil of uniform gradation within the limits of the system and that the end divisions contain the average percentage of material.

Div. No.	Name	Size, mm	Ratio of diameters	Ratio of surfaces	Ratio of volumes	Theoretical percentage of composition
1	gravel	> 1	-	-	-	12.5
2	coarse sand	1-0.32	3.2	10	32	12.5
3	medium sand	0.32-0.10	3.2	10	32	12.5
4	fine sand	0.10-0.032	3.2	10	32	12.5
5	coarse silt	0.032-0.010	3.2	10	32	12.5
6	medium silt	0.0100-0.0032	3.2	10	32	12.5
7	fine silt	0.0032-0.001	3.2	10	32	12.5
8	clay	< 0.001	-	-	-	12.5

He adopted a common factor of $\sqrt{10}$ (approximately 3.2) in passing from the smallest to the largest particle in all divisions of defined limits, therefore the ratios are all constant. The system can be expanded by using $\sqrt[4]{10}$ (approximately 1.8); each of the divisions defined above will be divided into two.

Extensive studies of soil properties were made in Sweden in the early part of this century by Atterberg (7, 8, 9, 10, 11, 12). He classified soil particles finer than 2 mm into five principal groups: 1) large sand grains which form water-permeable sands, 2) finer grains which form water retaining sands, 3) microscopic "silt" particles which form mud with rain and which display a certain cohesiveness on drying, 4) fine particles, or semicolloids which can be measured by a microscope, and which in water show the molecular motion characteristic of colloids and are coagulated easily by acids and salt, and 5) colloid particles which cannot be measured with a microscope. Since the 4th and 5th groups could not be quantitatively separated they were placed together into one group.

The particle size limit between water-permeable and water-retaining sands is not sharp. Atterberg placed it at 0.2 mm; sand from 0.5-0.2 mm diameter can retain only 30 mm of water, while sand from 0.2-0.1 mm can retain 110 mm of water above the capillary limit.

Atterberg placed the size limit between sand and silt at 0.02 mm for various reasons. Particles from 0.2-0.02 mm possess good capillarity and allow fast capillary movement of water. Materials finer than 0.02 mm show very high capillarity, but the movement of water in the capillaries is retarded. Also, 0.02 mm appears to be the upper boundary for the strong coagulation of fine materials in water containing acids or salts. This particle size is also about the limiting size that can be distinguished by the naked eye. Also, the boundary for the penetration of the root hairs of grasses into interspaces between soil grains occurs at grain sizes of about 0.02 mm.

The limit between silts and clays was placed at 0.002 mm primarily because particles smaller than this exhibit strong Brownian motion when settling from a water suspension. Grains of 0.002 mm are only weakly affected, those of 0.003 mm not at all. Also, materials finer than 0.002 mm show very retarded movement of water in the capillaries.

Atterberg placed the limit between sand and gravel at 2 mm because material larger than this has an insignificant capillarity. Stones of dimensions between 2-20 mm which may be moved about by wave action on beaches, he designated as pebbles. Larger stones, not rolled by waves, were called boulders.

Atterberg's main particle size limits were, therefore, 20, 2, 0.2, 0.02 and 0.002 mm. His complete classification was:

		Size
Boulders	Klipp block	> 2 m
	Stenblock	20-6 dm
	Blocksten	6-2 dm
Pebbles	coarse rock	20-6 cm
	broken stone	6-2 cm
gravel	coarse gravel	20-6 mm
	fine gravel	6-2 mm
sand	coarse sand	2-0.6 mm
	fine sand	0.6-0.2 mm
very fine sand	very fine sand	0.2-0.06 mm
	rock flour	0.06-0.02 mm
silt	silt	0.02-0.006 mm
	slime, silt, mud	0.006-0.002 mm
clay		< 0.002 mm

The limits for the subdivisions were set at 6 x powers of ten, since $2 \times \sqrt{10} = 6.32$ and $6.32 \times \sqrt{10} = 20$. 6.32 was rounded off to 6. These dimensions will plot as equal lengths on a logarithmetic scale.

Later Atterberg felt it would be advantageous to change the limits between coarse sand-fine sand, fine sand-silt, and silt-clay from 0.2, 0.02, and 0.002 mm to 0.3, 0.03, and 0.003 mm (7, 9). The limit between water-permeable and water-retaining sands is not sharp but lies at about 0.3 or 0.2 mm. The limit between macroscopic and microscopic particles is somewhat sharper; particles of 0.04 mm can be clearly distinguished with a magnifying glass, but those of 0.03 can hardly be. The root hairs of such plants as peas and beans are too large to penetrate between soil particles finer than 0.03 mm, although grass root hairs are limited at 0.02 mm. He found grains larger than 0.03 have the appearance of true sand grains, and smaller ones appear as dust. Since Brownian movement is affected by temperature, the size limit is not constant but probably lies near 0.003 mm. The 0.003 mm limit is also of great physiological significance in that most bacteria can not move between soil particles of smaller diameter.

The chief advantage to be found in changing the limits would be the length of time required to separate the fractions in a sediment analysis. When separating the fine clay from silt in the sediment analysis then in use, a settling time of 8 hours was required. Changing the limit to 0.003 mm would shorten this to 4 hours. Likewise, the settling time for separation of silt from fine sand would be shortened from 7 1/2 to 3 3/4 minutes by changing the limits from 0.02 to 0.03 mm.

Although Atterberg was in favor of the above changes, his originally defined limits gained wider usage. Later he expressed the opinion that the 0.2 mm limit was more nearly correct than 0.3 mm for the upper limit of water retaining sand (13).

The Atterberg system agreed fairly well with that proposed by Williams. In Atterberg's opinion the USDA system placed too much emphasis on the macroscopic particles and not enough on the microscopic portion, the limits should go lower than 0.005 mm, and the system had far too many divisions.

In 1914 an international commission on mechanical and physical soil investigations discussed a proposal to accept Atterberg's scale as an international system (40). The report indicates that Hilgard believed Atterberg's limits of 2.0-0.2 mm for coarse sand was too extensive, and suggested that coarse sand should be 2.0-0.5 mm, fine sand 0.2-0.02 mm and coarse and fine silt < 0.02 mm. In his opinion clay has no specific diameter, but practically it must include the silts finer than 0.0016 mm.

Dr. Frosterus recommended the following changes:

	Size, mm
gravel	20-2
coarse sand	2-0.2
fine sand	0.2-0.1
very fine sand	0.1-0.02
silt	0.02-0.002
clay	< 0.002

Coffey, Chairman of the American Society of Agronomy, recommended:

	Size, mm
coarse sand	2-0.7
medium sand	0.7-0.2
fine sand	0.2-0.07
coarse silt	0.07-0.02
medium and fine silt	0.02-0.002
clay	< 0.002

Whitney didn't see how Atterberg's system was any better or worse than any other. He thought the U. S. Bureau of Soils method should be given consideration.

Most of the members of the commission were in favor of Atterberg's methods, although a few wanted to use a different method for clay determination. Atterberg's scale was then accepted as the International System:

	Size, mm
gravel	> 2
coarse sand	2-0.2
fine sand	0.2-0.02
silt	0.02-0.002
clay	< 0.002

Hall and Russell (22), in 1911, presented a system which had been used in Great Britain for a number of years. It was as follows:

	Size, mm
fine gravel	> 1
coarse sand	1-0.2
fine sand	0.2-0.04
silt	0.04-0.01
fine silt	0.01-0.002
clay	< 0.002

The fractions, except for clay and part of the fine silt, do not represent distinct substances, so the limits are artificial.

Fine silt from 0.01-0.005 mm was considered to be of the same character as the coarser materials, although the silica content is less. The finer fraction, 0.005-0.002 mm has about 20 per cent less silica while the alumina, ferric oxide and potash contents increase.

Clay, < 0.002 mm, was considered a complex silicate or mixture of silicates, most important in determining soil fertility. It binds the soil and increases water holding capacity, depending on the amount of clay content present. The clay possesses properties of colloids while the fine silt does not.

Atterberg's scale was adopted by the Agricultural Education Association (Great Britain) in 1927 (38) and was adopted as the official British method in 1928 (37); however, a modified velocity scale was used. In Atterberg's system, material with an equivalent diameter of 0.002 mm was considered to have settled from a 10 cm height of water at $20^{o}C$ after a period of 8 hours, 0.02 mm equivalent diameter material settled out in 7 1/2 minutes, 0.2 mm material in 5 seconds (39). For the modified scale Atterberg's designation for 0.002 material was used as a base, and a particle that settled 10 cm in 8 hours in water at $20^{o}C$ was defined as 0.002 mm equivalent diameter. However, others were computed by Stoke's law on that basis. This gives 4 min. 48 sec. for 0.02 mm and 2.88 sec. for 0.2 mm, although in practice the last fraction is separated by sieving. The new scale was adopted because, since it was an international scale, widely used in the dominions and colonies, uniformity in scale for the Empire could be attained.

In the United States, conflicts often occurred between laboratory silt-clay limits of the U. S. Bureau of Soils System and textures determined by soil surveyors in the field. In 1936 Shaw and Alexander (41) reported results of a study in which soils were fractionated into silt 0.05-0.005, coarse clay 0.005-0.002, and fine clay or colloid < 0.002 mm groups. They found the coarse clay acted physically very like silt and several soil surveyors classified it as silt. Chemical tests showed that the silica content of the 0.005-0.002 mm fraction was more closely related to the silt than to the fine clay. They recommended changing the lower limit of silt to 0.002 mm.

Also, in 1936 Troug, Taylor, Simonson and Weeks (46, 47) recommended changing the lower limit of silt from 0.005 mm to 0.002 mm. Clay with an upper particle size limit of 0.002 mm is practically free of primary minerals such as feldspars, which weather easily. Certain minerals, such as quartz and muscovite, which are relatively resistant to chemical weathering, may be present both in primary and secondary form. Thus, clay less than 0.002 mm consists almost entirely of material which has great resistance to further decomposition. If separation is made at 0.005 mm, appreciable amounts of feldspar and other easily weathered minerals may be present.

In 1938 the USDA System was adopted with the silt range from 0.05-0.002 mm, and clay < 0.002 mm (30). Other limits were the same as in the older U. S. Bureau of Soils system. Later, in 1947, the size range from 2.0-1.0 mm was renamed "very coarse sand" rather than "fine gravel," and fine gravel is used for fragments from 2 mm - 1/2 inch in diameter (42).

SYSTEMS REPORTED IN ENGINEERING LITERATURE

In 1925 Terzaghi (45) set forth the system which evolved to what is known as the Continental System. His system was based in part on Atterberg's and in part on one proposed by the German committee in 1894 and presented on page 3 of this paper (14). Terzaghi recommended as follows:

	Size, mm
very coarse sand	2-1
coarse sand	1-0.5
medium sand	0.5-0.2
fine sand	0.2-0.1
coarse mo	0.1-0.05
fine mo	0.05-0.02
coarse silt	0.02-0.006
fine silt	0.006-0.002
coarse clay	0.002-0.0006
fine clay	0.0006-0.0002
ultra fine clay	< 0.0002

In the Continental System (19) the clay portion is reduced to one group of < 0.002 mm size. In addition particles larger than sand are defined thus:

	Size, mm
stone	> 30
coarse gravel	30-15
medium gravel	15-5
fine gravel	5-2

In early studies of sand-clay and topsoil roads in the United States the Bureau of Public Roads used the following definitions for various soil functions (15, 20, 26):

Sand - that portion of the soil passing the No. 10 sieve and retained on the No. 200 sieve (2.0-0.07 mm) which settles out of a 500 cc mixture of soil and water in 8 minutes. Coarse sand and fine sand were separated by the No. 60 sieve (0.25 mm).

Silt - that portion which passes the No. 200 sieve (0.07 mm) and settles out of the water suspension in 8 minutes.

Clay - that portion which passes the No. 200 sieve and remains in suspension after 8 minutes, but is thrown down by a centrifugal force equal to 500 g exerted for a period of one-half hour. This grain size is about 0.03 or 0.02 mm.

Suspension clay - that portion which remains in suspension after centrifuging.

The above limits were purely arbitrary and were used because of convenience of separation by the method then being used. These early size ranges were later supplemented by the following Bureau of Public Roads system (27):

	Size, mm	Sieve
gravel	> 2.0	(No. 10)
coarse sand	2-0.25	(No. 10 - No. 60)
fine sand	0.25-0.05	(No. 60 - No. 270)
silt	0.05-0.005	
clay	< 0.005	
colloids	< 0.001	

Later the limit between coarse sand and fine sand was changed to the No. 40 sieve, 0.42 mm (26).

Hogentogler (26) gave several reasons for the above system:

1) Use of the No. 40 sieve to separate coarse sand from fine sand eliminates one determination in the mechanical analysis since other tests for engineering properties of the finer portions are usually performed on the fraction passing the No. 40 sieve.

2) With the exception of the division between coarse and fine sands, the limits correspond to those of the U. S. Bureau of Soils system. This facilitates use of information in soil surveys made by that Bureau, in which the mechanical analysis plays an important part.

3) By using then present methods, the grading by the above sizes is as easily accomplished as were the former sizes by earlier methods.

4) Each division represents a group of particles having a special significance, listed as follows:

Gravel - rock fragments which are usually rounded by water action and abrasion. Quartz is the principal constituent. Gravel which is only slightly worn-rough and subangular commonly includes granite, schist, basalt or limestone.

Coarse sand - is likely to consist of the same minerals as the gravel. It is usually rounded like pebbles.

Fine sand - is usually more angular than coarse sand.

Silt - is composed of bulky grains, similar to fine sand except for size, and with the same mineral composition. However, it may be largely a product of chemical decay rather than of rock grinding and so may consist of silicates of aluminum and alkaline earths, and of oxides of iron. Sometimes the silt may be composed of foreign materials such as diatoms, pumice, or loess.

Clay - the coarser fractions usually and mainly consist of original fragments such as quartz and feldspar. However, clay consists almost entirely of the secondary products of chemical weathering. It differs from the coarser fractions in that it is the chemically reactive portion of the soil; the coarser fractions are inert.

Colloids - in a strict sense, are only those finer clay particles which show pronounced Brownian movement when suspended in water. Some authorities place the upper limit at 0.002 mm. In testing soils for highway purposes, colloids are considered as particles 0.001 mm in diameter and finer.

The American Society for Testing and Materials (4) and the American Association of State Highway Officials (1) originally used the same limits as the older Bureau of Public Roads system:

	Size, mm
particles larger than	2
coarse sand	2-0.25
fine sand	0.25-0.05
silt	0.05-0.005
clay	< 0.005
colloids	< 0.001

Later both of these organizations (2, 5) changed the limits of the coarser material to correspond with openings in the standard sieves used:

	Size, mm	Sieve
particles larger than	2	
coarse sand	2-0.42	(No. 10 - No. 40)
fine sand	0.42-0.074	(No. 40 - No. 200)
silt	0.074-0.005	
clay	< 0.005	
colloids	< 0.001	

In 1961 the ASTM method was again revised (6):

	Size, mm	Sieve
gravel	76.2-4.76	3"-No. 4 Sieve
coarse sand	4.76-2.00	No. 4 - No. 10
medium sand	2.00-0.42	No. 10 - No. 40
fine sand	0.42-0.074	No. 40 - No. 200
silt	0.074-0.005	
clay	< 0.005	
colloids	< 0.001	

The change of the limit between gravel and sand to the No. 4 sieve corresponds to that used for concrete aggregate.

In 1930, Gilboy originated a system which has gained wide engineering usage. It is commonly known as the M.I.T. system and has been adopted by the British as a standard system (33). His limits are:

	Size, mm
gravel	> 2
coarse sand	2-0.6
medium sand	0.6-0.2
fine sand	0.2-0.06
coarse silt	0.06-0.02
medium silt	0.02-0.006
fine silt	0.006-0.002
clay	< 0.002

This system was also recommended by Kopecky (18, 29) as early as 1914.

In 1947 the Civil Engineering division of the American Society of Engineering Education presented its definitions of the various soil components (35, 44). From an engineering point of view the primary difference between sand and gravel is in the size of the grains; particles of silt can not be readily distinguished by the unaided eye and silt exhibits considerable capillarity. The significant difference between silt and clay is that clay has plastic properties and silt does not. In fine-grained soils the influence of grain size is secondary to the influence of mineralogical and chemical composition. Therefore, gravel and sand should be defined on the basis of grain size; and sand and silt on grain size and capillarity; and silt and clay on plasticity.

In view of the general agreement of systems presently in use, such as the International, MIT and Public Roads Administration, the size limit between gravel and sand was defined at the No. 10 sieve (2.0 mm). Since the maximum size gravel generally used in highway and airport engineering is about 2 1/2 to 3 inches, the limit between boulders and gravel was placed at 3 inches (76.2 mm). The limit between sand and silt was put at the No. 200 sieve (0.074 mm) based on practical engineering considerations. The sand grains passing the No. 100 sieve and retained on the No. 200 are about the finest particles that can be easily distinguished by the unaided eye, and the No. 200 sieve is a practical limit of sieving in routine mechanical analysis.

As the portion of silt exceeds about 10 per cent of the total, capillarity becomes increasingly important, and is almost as significant in determining the properties and behavior of silts as is plasticity for clays, or the lack of capillarity for sands, since drainage and frost heaving properties of silts follow the same general patterns as capillarity. As little as 10 per cent finer than the No. 200 sieve considerably impedes drainage, more than 20 per cent silt makes the soil almost non-drainable.

A definite lower size limit for silt would be of great practical value because of the marked differences between silt and clay. These differences, however, are not due simply to grain size but to colloidal and other properties of clay. Silts are composed of fine mineral fragments which are altered very little from the parent material; clay minerals are formed by chemical weathering and decomposition. As yet there is no simple and satisfactory method for separating silt and clay because of an overlapping range of particle sizes which may or may not display properties of clay, and a definite size limit can not be established.

Non-plastic material passing the No. 200 sieve and with little or no strength when air dried is defined as silt. Material with plastic properties and considerable strength when air dried which passes the No. 200 sieve is clay-soil. The term "clay-soil" is used rather than "clay" since the silt admixture can not be separated out.

A practical set of definitions should give a reasonably accurate identification and description of the entire range of natural soils. Therefore, it is desirable to define coarse, medium, and fine fractions of the more coarse grained soil components.

The fractions of gravel and stone are by particle size only. Coarse gravel is that passing a 3" sieve (76.2 mm) and retained on a 1" sieve (25.4 mm). The largest permitted in base coarses is usually about 3 inches; in penetration macadam the material for the first course is usually between 2 1/2 to 1 1/4 inches.

Medium gravel is that passing the 1" sieve and retained on the 3/8" sieve (9.52 mm). The largest size permissable in surface courses of gravel, crushed rock, sand clay, gravel-clay, asphalt, and asphaltic concrete roads is from 3/4 to 1 inch. Material used for key and filter stone in dry-bound base courses and in penetration asphalt macadam varies from 1 to 3/8 inch.

Fine gravel is that passing the 3/8" sieve and retained on the No. 10 sieve (2.0 mm). Grit and pea gravel (passing the 1/4" sieve) are used in grouting and as filter materials in drainage wells. Fine gravel is used as "cover stone" for surface treatments of asphalt pavements.

Coarse sand is that material passing the No. 10 sieve and retained on the No. 30 (0.59 mm). It has a harsh, gritty feel.

Medium sand passes the No. 30 sieve and is retained on the No. 60 (0.25 mm). It is less gritty, but every grain can be felt. Beach sands are an example.

Fine sand passes the No. 60 sieve and is retained on the No. 200 (0.074 mm). It has a much softer and less gritty feel.

The silt component is divided into a coarse fraction, 0.074-0.02 mm, and a fine fraction, less than 0.02 mm.

The complete size limit breakdown is as follows:

	Size, mm	Sieve
coarse gravel	76.2-25.4	3"-1"
medium gravel	25.4-9.52	1"-3/8"
fine gravel	9.52-2.0	3/8"-No. 10
coarse sand	2.0-0.59	No. 10 - No. 30
medium sand	0.59-0.25	No. 30 - No. 60
fine sand	0.25-0.074	No. 60 - No. 200
coarse silt	0.074-0.02	< No. 200
fine silt	< 0.02 non-plastic	
clay	< 0.074 plastic	< No. 200

The U. S. Army Corps of Engineers and the U. S. Bureau of Reclamation use the Unified System of soil classification based on a proposal by Casagrande (18). In this system the grain size limits (43) are essentially the same as those reported in ASTM Standard D422-61T.

	Size, mm	Sieve
cobbles	> 76.2	3"
coarse gravel	76.2-19.5	3"-3/4"
fine gravel	19.5-4.76	3/4"-No. 4
medium sand	2.00-0.42	No. 10 - No. 40
fine sand	0.42-0.074	No. 40 - No. 200
fines (silt and clay)	< 0.074 (classified as to plasticity and cohesion)	< No. 200

SYSTEMS REPORTED IN GEOLOGICAL LITERATURE

In 1875 Orth presented the following system of grain size limits (51):

	Size, mm
gravel	> 3
very coarse sand	3-1
coarse sand	1-0.5
medium sand	0.5-0.25
fine sand	0.25-0.05
dust	0.05-0.01
finest dust	0.01

Diller (50), in 1898, used:

	Size, mm
gravel	> 2
fine gravel	2-1
coarse sand	1-0.5
medium sand	0.5-0.25
fine sand	0.25-0.10
very fine sand	0.10-0.05
silt	0.05-0.01
finest silt	0.01-0.005
clay	< 0.005

His system was later used by the New York City Aqueduct Commission, except that they designated coarse gravel as greater than 5 mm and fine gravel between 5 and 1 mm.

Perhaps most influential was the system of Udden (49), who in 1898 devised a scale in which the largest particle diameter of one grade was twice the largest diameter of the next lower grade.

	Size, mm
coarse gravel	8-4
gravel	4-2
fine gravel	2-1
coarse sand	1-1/2
medium sand	1/2-1/4
fine sand	1/4-1/8
very fine sand	1/8-1/16
coarse dust	1/16-1/32
medium dust	1/32-1/64
fine dust	1/64-1/128
very fine dust	1/128-1/256

No separations below 1/256 mm were made because only a very small portion of such small particles make up atmospheric deposits. Udden was reporting data on wind deposits. Separations down to 1/8 mm were made by sieving. Smaller particles were measured with a microscope.

Later, in a report on clastic sediments, Udden expanded his scale both upward and downward (48). For material larger than coarse gravel he used:

	Size, mm
very coarse gravel	8-16
very small boulders	16-32
small boulders	32-64
medium boulders	64-128
large boulders	128-256

For material smaller than very fine dust he used:

	Size, mm
coarse clay	1/256-1/512
medium clay	1/512-1/1024
fine clay	1/1024-1/2048

Keilhack (21, 51), in 1908, presented the following:

	Size, mm
gravel	> 2
very coarse sand	2-1
coarse sand	1-0.5
medium sand	0.5-0.2
fine sand	0.2-0.1
superfine sand	0.1-0.05
dust	0.05-0.01
finest dust	< 0.01

Boswell, in studying materials for glass industries in Great Britain used the following limits (32):

	Size, mm
gravel	> 2
very coarse sand	2-1
coarse sand	1.0-0.5
medium sand	0.5-0.25
fine sand	0.25-0.10
superfine sand or coarse silt	0.10-0.05
clay or mud	< 0.01

In 1913 Grabau (21) presented the systems of Diller, Keilhack, and several variations of these. From these systems he published the following scale to serve as a standard for comparison:

	Size, mm
boulders	> 150
cobbles	150-50
very coarse gravel	50-25
coarse gravel	25-5
fine gravel	5-2.5
very coarse sand	2.5-1.0
coarse sand	1.0-0.5
medium sand	0.5-0.25
fine sand	0.25-0.10
superfine sand	0.10-0.05
rock flour	0.05-0.01
superfine flour	0.01-0.005
clay size	0.005-0.001

Wentworth proposed a scale of grade and class terms for clastic sediments in 1922 (51). In fixing the limiting sizes he was governed by two considerations. First, there was a growing acceptance among geologists and engineers of a series of sieves for classification in which openings of consecutive sizes were in the ratio of 2 or $\sqrt{2}$, starting with a 1 mm standard. A geometrical series is ideal for the purpose, since a change of 1 inch is of the same significance and importance in the size of 10 inch cobbles as a change of 1/10 inch in the size of 1 inch pebbles. The use of a geometric series makes the successive grades fall into equal units on a logarithmic graph for easier reading and interpretation. Wentworth considered 2 as the most convenient ratio, and 1 mm as the most convenient and logical starting point. More minute subdivisions could be obtained by using $\sqrt{2}$, or $\sqrt[4]{2}$; these fit with and form subdivisions for the fundamental power series of 2.

His second consideration was to make the limits as close as possible to the common practice of the majority of geologists. He presented the systems of Keilhack, Grabau, Orth, Diller, U. S. Bureau of Soils, Baker, Udden, and New York City Aqueduct Commission as those in common use.

Wentworth selected the following limits conforming to a power series of 2 and which most closely agreed with standards of other authorities:

	Size, mm
boulder gravel	> 256
cobble gravel	256-64
pebble gravel	64-4
granule gravel	4-2
very coarse sand	2-1
coarse sand	1-1/2
medium sand	1/2-1/4
fine sand	1/4-1/8
very fine sand	1/8-1/16
silt	1/16-1/256
clay	< 1/256

Alling proposed a grade scale for sedimentary rocks in 1943 (3). He was looking for a convenient scale for use with thin sections and polished blocks, his scale is not meant for three-dimensional studies. Alling believed a satisfactory scale should have four fundamental properties: (1) the grain sizes should constitute a continuous series; (2) any division of the series will be arbitrary; (3) convenience of use is a criterion; and (4) statistical analysis requires the use of a constant geometric ratio.

He disagreed with Wentworth's contention that 2 was the most convenient constant ratio to use. Rather than 2, he preferred to use a constant ratio of 10. This places the limits for the major divisions at 0.0001, 0.001, 0.01, 0.1, 1, 10, 100 and 1000 mm. He used Hopkins proposal of a factor of $\sqrt[4]{10}$ for expanding the system (28). This divides each major division into 4 minor ones, all of which give sections of equal width when plotted on a logarithmetic scale.

Alling's proposed scale:

		Size, mm
Boulder	coarse	560-1000
	medium	320-560
	fine	180-320
	very fine	100-180
Cobble	coarse	56-100
	medium	32-56
	fine	18-32
	very fine	10-18
Gravel	coarse	5.6-10
	medium	3.2-5.6
	fine	1.8-3.2
	very fine	1.0-1.8
Sand	coarse	0.56-1.0
	medium	0.32-0.56
	fine	0.18-0.32
	very fine	0.10-0.18
Silt	coarse	0.056-0.10
	medium	0.032-0.056
	fine	0.018-0.032
	very fine	0.010-0.018

Clay	coarse	0.0056-0.010
	medium	0.0032-0.0056
	fine	0.0018-0.0032
	very fine	0.0010-0.0018
Colloid	coarse	0.00056-0.0010
	medium	0.00032-0.00056
	fine	0.00018-0.00032
	very fine	0.00010-0.00018

In 1947 a subcommittee on sediment terminology for the American Geophysical Union proposed a scale of grain sizes (36). This scale was made up after a survey of systems in use and recommendations of practicing geologists. The scale of sizes recommended is as follows:

	Size		
very large boulders	4096-2048 mm	or	160-80 in
large boulders	2048-1024		80-40
medium boulders	1024-512		40-20
small boulders	512-256		20-10
large cobbles	256-128		10-5
small cobbles	128-64		5-2.5
very coarse gravel	64-32		2.5-1.3
coarse gravel	32-16		1.3-0.6
medium gravel	16-8		0.6-0.3
fine gravel	8-4		0.3-0.16
very fine gravel	4-2		0.16-0.08 in.
very coarse sand	2-1		
coarse sand	1-1/2		1-0.500 mm
medium sand	1/2-1/4		0.500-0.250
fine sand	1/4-1/8		0.250-0.125
very fine sand	1/8-1/16		0.125-0.062
coarse silt	1/16-1/32		0.062-0.031
medium silt	1/32-1/64		0.031-0.016
fine silt	1/64-1/128		0.016-0.008
very fine silt	1/128-1/256		0.008-0.004
coarse clay size	1/256-1/512		0.004-0.0020
medium clay size	1/512-1/1024		0.0020-0.0010
fine clay size	1/1024-1/2048		0.0010-0.0005
very fine clay size	1/2048-1/4096 mm		0.0005-0.00024 mm

SUMMARY

All of the systems for designating particle-size limits are based on arbitrarily selected limits. Some investigators attempted to make their selections correspond with various properties of the soil fractions. In agricultural investigations such things as tillage properties, water retention, capillarity, penetration of plant roots, mineralogical and chemical composition, and colloidal properties were used as bases for various particle-size limits.

Early engineering systems were based on agricultural limits then in use. Some of the newer systems have particle-size limits which roughly correspond to materials used for specific engineering purposes. Engineering systems tend to evolve to the use of certain standard sieves for the particle-size limits, and often mix English and metric units of measure. The shape and slope of the particle-size distribution curve is considered to be of more importance than arbitrary grain-size limits. In some of the systems no size limit is placed between silt and clay, and the classification is made on the basis of plasticity and cohesion, which are more direct functions of clay mineralogy.

Some of the systems reported in geological literature are quite similar to those proposed by agriculturalists. Geological systems tend to follow a geometric series of particle-size limits, and sometimes define sizes in terms of their logarithms, such as "ϕ terms." The use of a constant geometric ratio (such as 2 or 10) makes the system more convenient to use and makes statistical analyses of data much easier.

PROSPECTUS

There are obvious advantages in having a standard particle-size limit system which would apply to all fields of endeavor. This would enable workers to use data from other sources without first translating it into their particular system.

In the writer's opinion, the first step in establishing such a standard system should be to determine the basis on which the particle-size limits are to be selected. The most logical basis would be the natural properties of the soil, such as permeability, capillarity, plasticity, and mineralogical and chemical composition and others.

The next step would be to define what is meant by the terms used to designate the various soil fractions. This is where the most difficulty will be found. First, the limits between the major soil components - gravel, sand, silt, and clay - should be defined and then the limits for subdivisions of the major components selected.

The systems commonly used now generally agree on 2 mm as the lower limit for gravel. A few engineering systems such as concrete technology use the No. 4 sieve (4.76 mm) for this limit, 4.76 to 2.0 mm being designated "coarse sand". The limits between sand and silt are more varied. Common sizes are 0.02, 0.05, 0.06, 0.062 and 0.074 mm. The 0.02 mm limit, however, is not widely used in this country. Common limits between silt and clay are 0.002, 0.005 and 0.004 mm. Some engineering systems do not use a particle-size limit but base this division on plasticity and cohesion.

The limits commonly used for subdividing the major components are even more varied. Even here some of the limits are approximately the same, but different terms are used to describe the fractions thus separated. Some systems employ many more subdivisions than do others.

To reach agreement on what constitutes the "natural limits" of a soil will be difficult. Compromise by all sides will be required, since what is considered an obvious limit by one group may be quite different from the ideas of others. If a system attempts to include all of the limits which may be desired by various groups it will soon become unwieldy and defeat the purpose for which it is designed. The number of limits should be kept at a minimum, which will assure ease of analysis and still present the desired information.

Whenever attempts are made to establish a standard system of particle-size limits, the users of some of the existing systems argue that they can not afford to change because of the amount of data already accumulated using their particular scheme. For example, the USDA refused to go along with the decision to make Atterberg's system an international standard because of the tremendous volume of data catalogued in the U. S. Bureau of Soils system. Since that time the USDA has changed the lower limit of the gravel from 1 to 2 mm and the lower limit of silt from 0.005 to 0.002 mm, both of which are in agreement with the International System. The only major division on which the two systems now disagree is the limit between sand and silt; the USDA system places it at 0.05 mm, the International system at 0.02 mm. Had the changes been made in 1914, much less data would have accumulated under the older limits. Therefore, if it can be shown that certain limits are more desirable, it can be shown to be to an organization's advantage to change at once rather than wait until some later time.

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