AN AIR ELUTRIATOR FOR DETERMINING THE DRY AGGREGATE SOIL STRUCTURE IN RELATION TO ERODIBILITY BY WIND[1]

W. S. CHEPIL

U. S. Department of Agriculture

Received for publication September 7, 1950

The erodibility of soil by wind is dependent on the state and stability of the dry aggregate structure. Development of suitable methods of determining the dry aggregate soil structure has, however, received little attention in the past. A method of dry aggregate analysis used to an appreciable extent consisted of sieving the soil in air and finding the weight of the aggregates or clods on each sieve. Keen (4) and Mangelsdorff (5) placed the soil on a nest of sieves and shook the nest by hand. To avoid serious discrepancies due to personal judgment as to the amount of shaking required, Volkov (7) and Cole (3) passed the air-dry soil through a nest of flat sieves operated mechanically by a motor giving a standard number of shakes and jolts. The jolting action is rather severe, however, and tends to break up the weak clods. Moreover, the flat sieves, especially the fine ones, often clog up badly, thereby virtually nullifying the effect of sieving. To overcome these difficulties, Chepil and Bisal (1) devised a rotary sieve.

The rotary sieve has been used in wind erosion studies as a dependable device for determining the size distribution of dry soil particles and aggregates. As these studies progressed, however, it became apparent that an accurate evaluation of erodibility necessitates a knowledge not only of the size distribution of dry soil particles and aggregates but also of the apparent density of these units. It became necessary, therefore, to determine the apparent density of all the fractions separated by dry-sieving. Moreover, it was essential for detailed study to determine the amount and apparent density of at least 12 erodible and several non-erodible size-fractions contained in the soil. The original rotary sieve failed to meet this requirement, since it was capable of separating the soil into a maximum of seven fractions, of which only two were erodible.

Because of the limitations of the sieve, a method of estimating the erodibility of soils by wind based mainly on the elutriation procedure and only in a limited degree on dry-sieving has been devised. An air elutriator has been designed, constructed, and tested thoroughly for this purpose. The elutriator facilitates a convenient determination of the amount of any desired number of size-fractions contained in the soil without resorting to a separate determination of apparent density of each of these fractions. The elutriator is described herein.

DESCRIPTION OF THE ELUTRIATOR

The elutriator consists of a 6.5-inch diameter transparent vertical duct A (fig. 1) connected to a blower B run by $\frac{1}{3}$-horsepower electric motor. At the base

[1] Contribution No. 429, department of agronomy, Kansas Agricultural Experiment Station, Manhattan, and the Soil Conservation Service, U. S. Department of Agriculture. Cooperative research in the mechanics of wind erosion.

of the duct, a cotton-cloth filter C is used. Immediately above the filter a 300-mesh sieve D is fixed to the transparent plastic duct A. The soil sample to be elutriated is placed on this sieve.

The control of the wind is obtained by varying the thickness of the cloth filter C and by increasing the cross-sectional area of the air inlet opening E. A metal plate F fitted snugly against the opening and attached to a lever G pivoted at

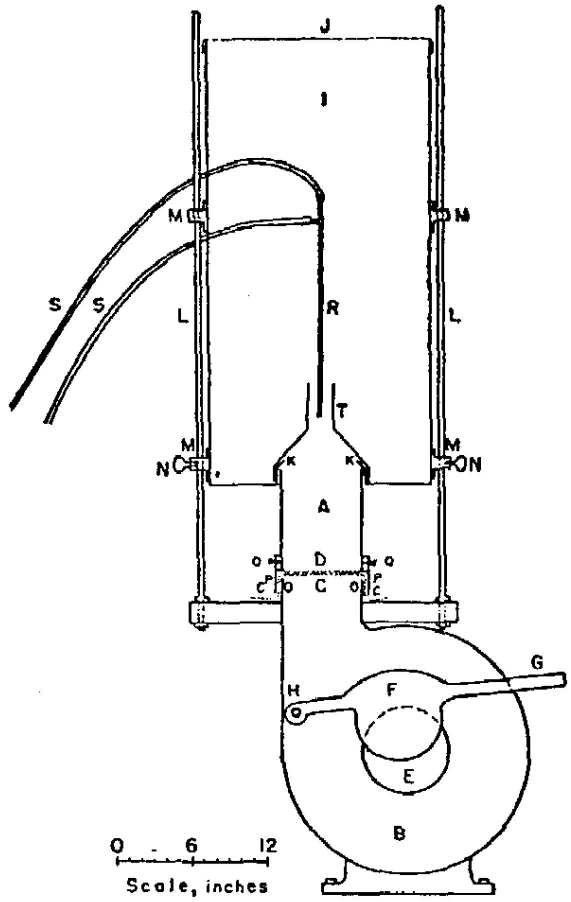

FIG. 1. DIAGRAMMATIC REPRESENTATION OF THE AIR ELUTRIATOR

H can be moved up or down for any amount of opening desired. The following cloth filters are used to produce ranges of wind velocity as follows:

MATERIAL	PLY	OZ./SQ. YD.	VELOCITY IN CM./SEC.
Duck	4	12	<20
Duck	1	12	20–60
Cloth	2	8	60–150
Cloth	1	8	150–300
Cloth	2	6	300–450
Cloth	1	6	450–600

No cloth for velocity greater than 600 cm./sec.

The soil fractions blown up and out of the duct *A* settle on the floor of a cylindrical dust chamber *I*. The dust chamber is equipped with a door (omitted from figure 1 but shown opened in figure 2) to facilitate cleaning out the chamber and measuring the wind velocity. The top of the cylinder at *J* is covered with a

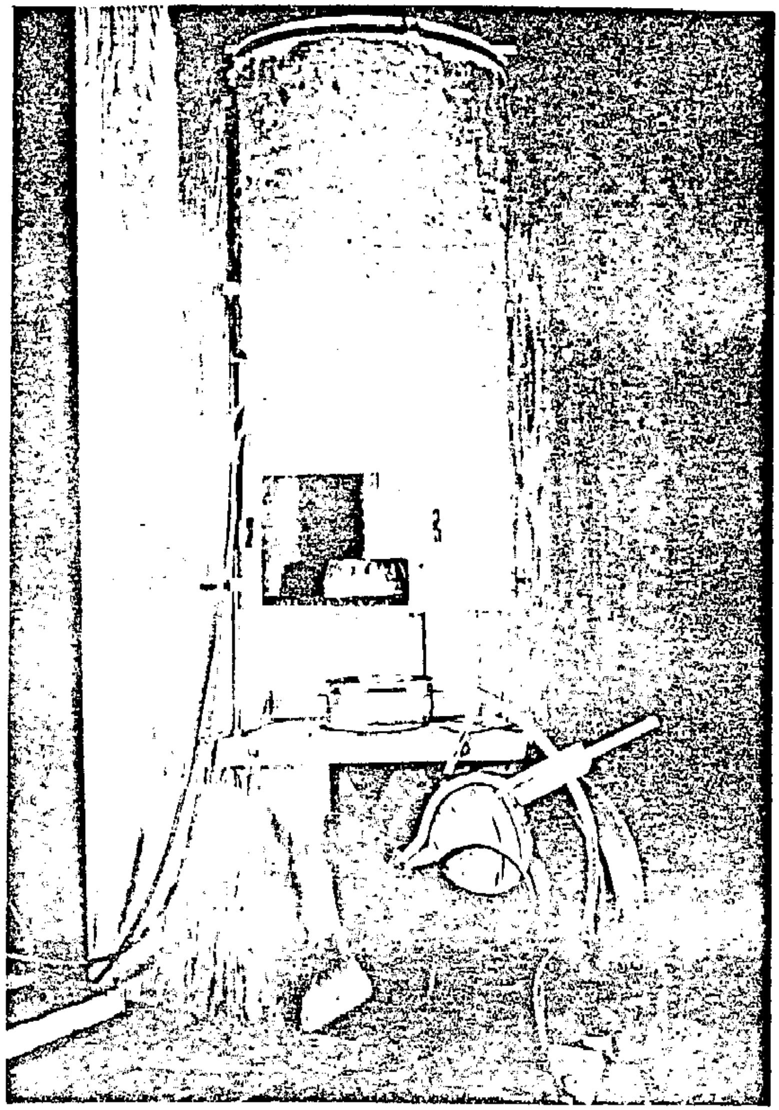

FIG. 2. THE AIR ELUTRIATOR

cloth of fine porosity. The cloth blocks the upward passage of most of the dust, allowing the air to pass through.

During elutriation, the weight of the dust collection chamber *I* is supported by a circular flange *K* fitted closely against the top of the cylindrical duct *A*. The chamber is held in place laterally by two fixed vertical shafts *L* passing through four bearings fastened to the chamber at M. To facilitate placement of soil in or removal from D, the dust collection chamber is pushed up and the weight of the chamber is supported at any desired height by tightening the thumb screws N against the two vertical shafts at M.

The elutriator duct A is detachable from the blower B. When in place, it is held tightly against the blower outlet and the cloth filter at O by a pair of springs mounted on an expanding sleeve P, which is held firmly against the elutriator duct by three screws at approximate positions Q.

The vertical velocity of the wind is measured with a Pitot tube R connected by rubber tubing S to an alcohol manometer not shown in figure 1. The manometer is adjusted to a 0.5-, 1-, or a 2-degree slope, depending on wind velocity. To facilitate a measurement of wind velocity as low as 5 cm. per second, a funnel, as shown by T, is used. The funnel constricts the cross-sectional area of the vertical duct from a 6.5- to a 2-inch diameter. The effective portion of the Pitot tube is in the 2-inch section. For measurement of high wind velocities, funnel T is removed and the Pitot tube is lowered into the elutriator duct A so that the lower end of the tube is 1 inch below the top of the elutriator duct.

The purpose of the flange K, besides that of supporting the dust-collecting chamber, is to speed up the velocity of the wind above the elutriator duct. The speed-up of velocity at this position prevents the suspended soil fractions from falling back into the duct after they have entered the dust-collecting chamber I.

The vertical velocity of the wind along the whole cross-sectional area, except within about 1 mm. from the wall of the elutriator duct, is remarkably uniform. This uniformity is due to the air pressure exerted by the blower against the cloth filters or the fine sieve or both. The total pressure-head against the cloth filters and the sieve ranges from 0.7 to 7 inches of water, and against the sieve alone from 0.2 to 3 inches of water, depending on the size of opening of the inlet vane.

OPERATION OF THE ELUTRIATOR

In the elutriator is placed 250 gm. of the soil which passed through a 6.4-mm. sieve. A very low vertical wind velocity sufficient to remove the fine dust particles is applied first, the residual sample is weighed and, after exposure to a slightly higher velocity, is weighed again. This process of weighing the soil after each increment increase in velocity is repeated until a velocity capable of removing soil aggregates much larger than those usually transported by atmospheric wind is reached. The usual velocities applied are sufficient to lift quartz grains with diameters of 0.044, 0.074, 0.1, 0.15, 0.18, 0.25, 0.30, 0.42, 0.59, 0.84, 1.19, 1.68, and 2 mm. These sizes, starting with 0.074 mm., conform to the U. S. Bureau of Standards sieve scale with openings increasing in a ratio of the square root of 2, or 1.414, except in three instances where closer sizing was desired. The time required to remove all particles smaller than 0.044 mm. and smaller than 0.074 mm. is 3 and 1 minutes, respectively, with gentle stirring with a soft, narrow hair brush. Thirty seconds without stirring is allowed for all other sizes.

The fraction remaining in the elutriator is then weighed and the weight expressed in percentage of the total weight of the soil elutriated. Size fractions greater than 6.4 mm. are determined by sieving, and the apparent density and volume of these fractions are determined from the bulk density method described previously (2).

The elutriator facilitates the measurement of a vertical air velocity required barely to lift the various equivalent sizes of dry soil particles and aggregates. The force required to lift the aggregate exceeds slightly, and for practical purposes may be considered equal to, the downward pull of gravity. The force of gravity depends on the mass of the aggregate. The force of the air stream required to lift the aggregate, on the other hand, depends on the size, shape, and apparent density of the aggregate. The size usually is represented by the average diameter, whereas the apparent density is designated by the proportion which a weight of a given volume of the aggregate bears to the weight of an equal volume of water. It is virtually impossible to describe a shape, such as that of a natural soil aggregate. It is necessary, therefore, to express the results of elutriation in terms of the equivalent diameter of the component soil aggregates, rather than in terms of the actual diameter, apparent density, and shape. The equivalent diameter, as determined for soils by elutriation, is a diameter of a standard quartz grain of a particular size, shape, and apparent density which requires the same velocity of elutriation as the soil units. The vertical velocity of elutriation and the horizontal velocity connected with erodibility (2) were found to vary directly with each other. Consequently, the equivalent diameter can be defined also as a diameter of a standard quartz grain which has an apparent density of 2.65 and an erodibility equal to that of a discrete soil unit of some particular diameter and apparent density. It is equal to $\frac{\sigma d}{2.65}$ where σ is the apparent density of a discrete soil unit of diameter d. Ottawa sand, obtainable commercially, and washed alluvial silt were chosen as the standard. The shape of the Ottawa sand and of the alluvial silt of any diameter is nearly round, the bulk density is about 1.53, and the apparent and real density is about 2.65 (2). Ottawa sand was separated into different size-fractions by direct sieving. The silt was extracted from the alluvium first by dispersion of the alluvium and then by repeated sedimentation and decantation of the supernatant suspension.

The vertical velocity of elutriation and the horizontal velocity connected with erodibility vary with each other, provided the air turbulence, the nature and degree of surface roughness, and numerous other possible conditions of the air and of the soil remain the same. In the field, these conditions vary considerably. It is evident that the elutriator can be used, at best, as a tool for measuring only the relative erodibility of the soil.

QUALITATIVE PERFORMANCE OF THE ELUTRIATOR

The fact that different thicknesses of cloth filter were used to produce different vertical wind velocities raises a question whether a different performance in soil transport is associated with the amount of cloth for a given velocity. The vertical velocity required to lift silt particles and Ottawa sand grains of various diameters is shown in figure 3. The velocity shown in figure 3 was recorded on several occasions with somewhat different thicknesses of cloth filter. The velocity required to lift a given diameter was found repeatedly to be virtually the same. The size of the standard sand lifted out of the elutriator duct was apparently dependent on the measured vertical velocity of the wind and not directly on the thickness of the cloth filter.

A second consideration pertaining to the dependability of the elutriator is connected with the question of how well individual results of elutriation can be reproduced for the same soil. Table 1 shows the results of elutriation repeated

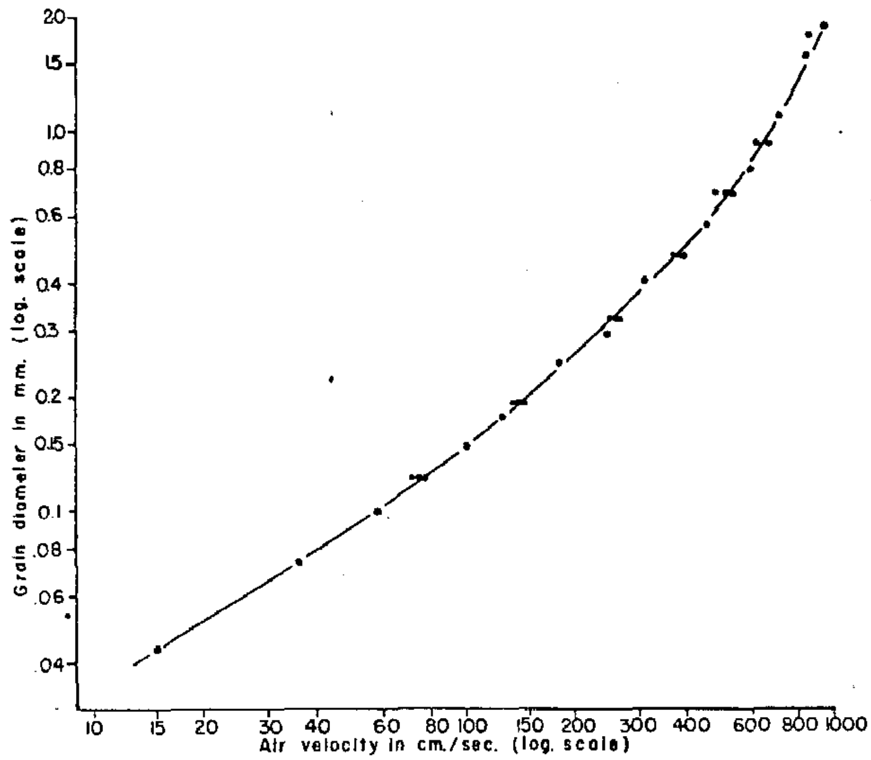

FIG. 3. VERTICAL AIR VELOCITY REQUIRED TO LIFT QUARTZ GRAINS OF VARIOUS DIAMETERS IN THE ELUTRIATOR

on two soils four times. Although the percentage of each size-fraction varied considerably among the four series of tests, the mean weighted equivalent diameter was fairly uniform for each soil. It will be seen that the largest deviation from the mean among all of the determined increments of equivalent diameter in the two soils was 3.4 per cent, and the smallest was 0.3 per cent. The weighted mean equivalent diameters for soils A and B were 0.51 mm. and 0.78 mm., and the maximum deviations from the mean were 0.10 mm. and 0.05 mm., respectively. The results of elutriation are apparently reproducible.

A third consideration is whether the elutriator has the same performance regardless of amount, size, and proportion of discrete soil units being elutriated.

Since a substantial pressure head was exerted against the filters and the soil body, a variation in the volume of the soil units at the bottom of the elutriator duct had no appreciable effect on the volume of the air coming out at the top of the duct. If the velocity was increased gradually during elutriation, the concentration of soil units at the top of the duct was always negligible. Consequently the velocity at that level remained the same for the same filters and opening of the inlet vane, irrespective of the volume of the soil that was put at the bottom of the elutriator duct. These facts are confirmed by results in table 2.

TABLE 1

Results of repeated elutriation on two soils

EQUIVALENT DIAMETER	SOIL A						SOIL B					
	Distribution					Maximum deviation from mean	Distribution					Maximum deviation from mean
	1	2	3	4	Mean		1	2	3	4	Mean	
mm.	%	%	%	%	%	%	%	%	%	%	%	%
<0.044	4.7	6.3	5.4	4.9	5.3	1.0	3.1	1.8	1.6	2.8	2.3	0.8
0.044–0.074	15.7	15.9	15.5	15.2	15.6	0.4	2.9	4.2	3.7	3.3	3.5	0.7
0.074–0.1	7.8	10.3	8.9	9.6	9.2	1.4	3.6	2.8	3.6	2.9	3.2	0.4
0.1–0.15	14.2	13.0	14.2	11.5	13.2	1.7	12.3	11.6	12.5	11.2	11.9	0.7
0.15–0.18	3.7	4.4	3.3	3.7	3.8	0.6	7.2	6.0	6.4	6.9	6.6	0.6
0.18–0.25	13.9	9.7	11.3	10.0	11.2	2.7	13.9	14.3	14.0	13.6	14.0	0.4
0.25–0.30	4.4	9.6	9.5	7.9	7.8	3.4	4.4	7.9	6.1	6.7	6.3	1.9
0.30–0.42	9.2	9.2	8.6	9.1	9.0	0.4	16.9	15.9	17.1	14.7	16.2	1.5
0.42–0.59	4.8	6.4	4.7	6.5	5.6	0.9	8.8	6.0	6.9	8.7	7.6	1.6
0.59–0.84	3.3	3.3	3.2	3.7	3.4	0.3	4.0	4.4	3.9	4.1	4.1	0.3
0.84–1.19	6.3	2.8	6.0	4.7	5.0	2.2	3.8	7.3	4.5	6.5	5.5	1.8
1.19–1.68	3.2	3.6	3.0	4.5	3.6	0.9	5.5	6.8	8.3	8.6	7.3	1.8
1.68–2.0	2.7	3.5	2.9	4.1	3.3	1.4	2.7	3.0	2.9	2.1	2.7	0.6
>2.0*	6.1	2.0	3.6	4.8	4.1	2.1	10.9	7.8	8.5	8.0	8.8	2.1
Weighted average equivalent diameter.... *mm.*	0.58	0.41	0.48	0.56	0.51	0.10	0.83	0.76	0.78	0.77	0.78	0.05

* Average assumed to be 4.2 mm.

The results in table 2 demonstrate that varying amounts of soil up to 400 gm., or 260 ml., have no apparent effect on the results of elutriation. Results on samples 1 and 2 show that irrespective of whether the amount of sand taken was 100 or 250 gm., the proportion of a given size of sand unit blown out of the elutriator under a given velocity was virtually the same. This was true provided the velocity of elutriation was very low at first and was increased gradually until a desired velocity was reached. Thus, when 100 gm. of the standard quartz sand (sample 1) that passed through a 0.25-mm. sieve was exposed to a 100 cm./sec. air velocity, the amount left in the elutriator was 25.6 gm. On the other hand, when 250 gm. was taken (sample 2), the amount that remained in the elutriator was 63.0 gm. or, on a proportional basis, virtually the same as in sample 1. It is shown, furthermore, that the proportion of a given size of soil unit blown out of the elutriator under a given velocity is virtually the same irrespective of the range of size of the soil units in the sample that is being elutriated. Thus, when 100 gm. of sand was mixed with 150 gm. of comparatively large silt loam aggregates not removable from the elutriator by the air velocity applied, the amount of sand that remained in the elutriator after exposure to a given wind was virtually the same as where the same sand alone was used (samples 3 and 4).

A slight discrepancy not directly due to the performance of the elutriator is reflected in the results in table 2. It will be seen that a velocity of 180 cm./sec. was sufficient to remove all but a trace of sand in samples 1 and 2. The trace was relatively small proportion of sand of about 0.25 mm. made up of a heavier-than-quartz mineral distinctly darker and readily distinguishable from the quartz

TABLE 2

Elutriator performance with different amounts and proportions of discrete soil units

SAMPLE NUMBER	MATERIALS AND AMOUNTS	AMOUNT REMAINING IN THE ELUTRIATOR AFTER EXPOSURE TO AN AIR VELOCITY OF					
		10 cm./sec.			180 cm./sec.		
		1	2	Average	1	2	Average
		gm.	gm.	gm.	gm.	gm.	gm.
1	100 gm. of dune sand ranging up to 0.25 mm. in diameter	23.1	28.0	25.6	0.2	0.2	0.2
2	250 gm. of above sand	65.7	60.3	63.0	0.5	0.6	0.55
3	100 gm. of above sand and 150 gm. of irremovable silt loam aggregates 2.0–6.4 mm. in diameter	173.4	174.4	173.9	149.2	149.3	149.2*
4	250 gm. of above sand and 150 gm. of the silt loam aggregates	212.0	213.0	212.5	148.6	148.2	148.4†

*0.15 gm. of which was dune sand.
† 0.1 gm. of which was dune sand.

grains. Since in samples 3 and 4 the same quantity of sand mixed with 150 gm. of irremovable silt loam aggregates was used, it is logical to expect that the amount left in the elutriator would be equal to 150 gm. of silt loam aggregates plus a trace of the sand. Actually the total weight was slightly less than 150 gm. The loss was due to abrasion of the silt loam aggregates during elutriation. This loss was not appreciable, however, and was considerably smaller than the loss obtained when the aggregates were shaken for an equal time on a sieve.

The silt loam aggregates that remained in the elutriator were shaken on a 0.25-mm. sieve. The abraded portion that passed through the sieve was elutriated at the same velocity as before. A trace of dark colored sand identical to that found after elutriation in samples 1 and 2, and not found in the silt aggregates, was recovered in every case. This trace of sand was unmistakably identified as that portion originally belonging to the sand. The effects of elutriation on sand were, therefore, the same, irrespective of the presence or absence in the elutriator of a comparatively large proportion of other irremovable soil units.

COMPARISON OF RESULTS OBTAINED WITH THE ELUTRIATOR AND WITH DRY-SIEVING

A comparison of equivalent diameter distribution of dry soil aggregates determined by elutriation and by hand sieving can be made from the results which

TABLE 3

Comparison of equivalent diameter distribution of dry soil aggregates determined by elutriation and by sieving

BY ELUTRIATOR			BY SIEVING						
Equivalent diameter	Soil A	Soil B	Actual diameter	Soil A			Soil B		
	Amount	Amount		Apparent density*	Average equivalent diameter†	Amount	Apparent density*	Average equivalent diameter†	Amount
mm.	%	%	*mm*		*mm.*	%		*mm.*	%
<0.044	5.3	2.3	<0.044	2.09	0.017	8.7	2.01	0.017	2.3
0.044–0.074	15.6	3.5	0.044–0.074	2.08	0.046	8.4	1.87	0.042	1.2
0.074–0.1	9.2	3.2	0.074–0.1	2.07	0.068	5.1	1.68	0.055	1.2
0.1–0.15	13.2	11.9	0.1–0.15	2.06	0.097	10.3	1.68	0.079	3.8
0.15–0.18	3.8	6.6	0.15–0.18	2.17	0.135	5.5	1.65	0.103	2.7
0.18–0.25	11.2	14.0	0.18–0.25	2.14	0.174	12.4	1.68	0.136	9.1
0.25–0.30	7.8	6.3	0.25–0.30	2.08	0.216	6.4	1.68	0.174	7.4
0.30–0.42	9.0	16.2	0.30–0.42	1.94	0.264	8.9	1.71	0.232	16.8
0.42–0.59	5.6	7.6	0.42–0.59	1.77	0.337	6.7	1.68	0.320	13.9
0.59–0.84	3.4	4.1	0.59–0.84	1.66	0.448	5.5	1.63	0.440	7.9
0.84–1.19	5.0	5.5	0.84–1.19	1.49	0.571	3.1	1.58	0.605	2.1
1.19–1.68	3.6	7.3	1.19–1.68	1.46	0.790	3.1	1.47	0.796	1.8
1.68–2.0	3.3	2.7	1.68–2.0	1.47	1.021	2.7	1.59	1.104	3.9
>2.0	4.1	8.8	2.0–6.4	1.51	2.393	13.2	1.59	2.520	25.9
Weighted average equivalent diameter.......... *mm.*	0.51	0.78			0.52			0.87	

* Apparent density of discrete soil units is equal to $2.65 \frac{\rho}{1.53}$ in which ρ is the bulk density of the sieve fraction.

† Equivalent diameter is equal to $\frac{\sigma d}{2.65}$ in which σ is the apparent density of discrete soil units of average diameter d.

were obtained on two widely different soils shown in table 3. The weighted average equivalent diameter determined by the elutriator was 0.51 mm. for soil A and 0.78 mm. for soil B; by sieving it was 0.52 and 0.87 mm., respectively. Sieving in both cases gave a slightly higher average equivalent diameter than elutriation. The percentage difference was greater for soil B than for soil A. Because of the shape of the soil grains, both the magnitude and the trend of these differences vary as expected. The standard quartz grains are uniformly rounded. Particles and aggregates in soil A, which was a sandy loam, were slightly more angular; whereas those of soil B, a clay, were composed almost entirely of sharp-cornered, irregularly shaped fragments broken off larger aggregates by a recent action of wetting and drying and freezing and thawing.

Obviously, the greater the angularity of the discrete soil fractions, the lower was the velocity required to lift them and, consequently, the lower was their equivalent diameter. The differences in the average equivalent diameter determined by the two methods were not great, however, and seem to indicate that shape is a minor factor in the transport of erodible units by wind. Apart from these slight differences, the results of analysis by elutriation compare favorably with the results of sieving. The elutriation required only about 50 per cent of the total time needed for sieving and for determining the apparent density of the soil particles and aggregates in each sieve grade.

Since sieving was done by hand, errors likely occurred, depending on the amount of judgment and vigor of the individual performing the sieving. A nest of 14 sieves was used. This number is too great to incorporate into a rotary sieve of the type that was originally designed. The elutriator, on the other hand, can perform conveniently tasks for which a virtually infinite number of sieves of different openings might be required.

The size distribution of soil particles smaller than 0.1 mm. in equivalent diameter can be determined conveniently with the elutriator. Such determinations carried out with flat sieves, on the other hand, are extremely laborious.

DISCUSSIONS AND CONCLUSIONS

The vertical velocity required to lift different sizes of standard sand corresponds closely to the generally accepted terminal velocity of fall of quartz spheres in air (6, pp. 57–64) for grains up to 0.6 mm. in diameter. For grains above this size the vertical velocity becomes increasingly smaller than the terminal velocity of fall. The discrepancy probably is due to the turbulent nature of the air stream in the elutriator. This discrepancy, however, has nothing to do with the reliability of the elutriator. It is merely necessary that each elutriator be calibrated for vertical velocities required to lift the standard grains and to express the equivalent diameter of the soil fractions elutriated in terms of the diameter of the standard grains.

The major advantages of the air elutriator over a nest of sieves for determining the dry aggregate soil structure seem to be as follows:

1. The air elutriator facilitates a convenient determination of the equivalent diameter of the erodible soil units. It thereby obviates the necessity of running a separate determination of apparent density.
2. The proportion of the soil above and below any equivalent diameter can be determined readily with the elutriator. With sieves, only the proportion of the soil above and below a limited number of fixed diameters, which often have no relationship to the equivalent diameter, can be determined.
3. Contrary to the sieving technique, the elutriator facilitates the determination of the possible effects of shape of the discrete soil units on erodibility.

4. The distribution of fine dust can be determined somewhat more readily on the elutriator than by sieving.
5. Soil aggregates are less abraded on the elutriator than on sieves, especially on a nest of flat sieves.

Some of the drawbacks or imperfections of the elutriator are as follows:

1. A sudden increase of velocity in the elutriator causes an upward burst of a mass of soil units. This causes the removal of some soil units larger than the ones which would have been removed if the velocity were increased gradually. This type of error is dependent on the degree of care exercised by the operator. Contrary to results from the rotary sieve (1), the results of elutriation may be influenced by a personal factor.
2. The results of elutriation are not so consistent as those with the rotary sieve. They may be equally consistent with those determined with a next of flat sieves.
3. The elutriator determines the equivalent diameter of discrete soil units on the basis of air velocity applied. The air velocity has to be watched carefully during elutriation and adjusted if and as necessary. The sieves, on the other hand, have a fixed size of opening which needs no watching.

REFERENCES

(1) Chepil, W. S., and Bisal, F. 1943 A rotary sieve method for determining the size distribution of soil clods. *Soil Sci.* 56: 95–100.

(2) Chepil, W. S. 1950 Methods of estimating apparent density of discrete soil grains and aggregates. *Soil Sci.* 70: 351–362.

(3) Cole, R. C. 1939 Soil macrostructure as affected by cultural treatments. *Hilgardia* 12: 429–472.

(4) Keen, B. A. 1933 Experimental methods for the study of soil cultivation. *Empire Jour. Exp. Agr.* 1: 97–102.

(5) Mangelsdorff, E. G. 1929 Experiments on soil cultivation. *Landw. Jahrb.* 69: 485–519.

(6) Rouse, H. 1937 Nomogram for settling velocity of spheres. Exhibit D, Report of the Committee of Sedimentation, National Research Council, Washington, D. C.

(7) Volkov, M. I. 1933 On the methods of determination of soil structure. *Pedology* 1: 52–58.