Aerodynamics of Wind Erosion

By A. W. Zingg and W. S. Chepil
MEMBER A.S.A.E.

THE dynamic action of fluids on the land surface takes many forms. While all of them are in some measure geological processes, they may assume economic importance through, or to, the activities of man.

The problems may be the accelerated downslope movement of soil by surface runoff or rainfall impact on cultivated lands. It may consist of the beating of wind-formed waves eroding the materials along a highly developed shore line. Again, it may be the distribution of drifting snow affecting the snow-melt from mountainous areas or the distribution of moisture in prairie regions. It may be the rolling of sediment along the beds of streams and rivers. Finally, exposed soils may be moved bodily by the action of the wind.

Basically, all of these phenomena present related research problems: namely, (a) the determination of the incidence and nature of a fluid force near the interfaces of fluid and solid media, and (b) the determination of the properties of the material in question to resist the fluid force. Methods of control must strive (a) to modify the force on the material susceptible to movement or transportation by the fluid or (b) to modify the material either to increase or to decrease its detachability.

As early as 1911, Free(5)* published a bibliography of aeolian geography. It contains 2,475 references having to do with phenomena related to wind and soil formation, transportation, detachment, etc. It is interesting to note that approximately 75 per cent of the articles listed are of foreign origin. Again, in 1941, Malina(11) published a review paper, entitled "Recent Development in the Dynamics of Wind Erosion." This paper contains 59 references and is an excellent summary of developments to that date.

Due to limited funds and the large turnover of research personnel during the war years, fundamental research on the problem was at a low ebb in the United States. Gone also was the combination of drought, high winds, and general economic distress which spotlighted the problems of the plains area in the thirties.

The following statements can be made regarding our approaches to the wind erosion problem in general:

1 Progress has been made in developing controls, more or less by trial-and-error methods in the field. We do not have, however, the basic information on the relationship between wind, soil, vegetative cover, and topography that is necessary to design preventive measures.

2 At the present time, we must look chiefly to the works of investigators in other countries or to studies in allied fields of endeavor for a body of fundamental information bearing on the subject.

3 The problem of soil movement by wind in the United States is undoubtedly of less over-all economic importance than that of soil erosion by intense rainfall. Perhaps for this reason, research on the problem has received little attention

Professor James C. Malin(10), historian of the University of Kansas, has stated: ". . . both the relative frequency and severity of the dust storms were grossly misrepresented during the drought period of the 1930's and the public and scientific world are badly informed about the whole subject."

The High Plains Wind Erosion Laboratory. A study of the mechanics of wind erosion was initiated at Kansas State College, Manhattan, in the late fall of 1947. Research on the problem deals with the fundamentals of the movement of soil by wind in the high plains area. Administratively the project is a cooperative one between the Kansas Agricultural Experiment Station and the research division of the Soil Conservation Service. Work is centered in the Department of Agronomy of the Kansas station. Studies are regional in character.

Objectives of the research are as follows:

1 To determine the causative factors of wind erosion, and the processes by which soil materials are moved and transported by wind.

2 To develop suitable methods for studying the phenomenon of wind erosion.

3 To determine the effects of physical and chemical soil properties, such as structure, texture, kind and amount of

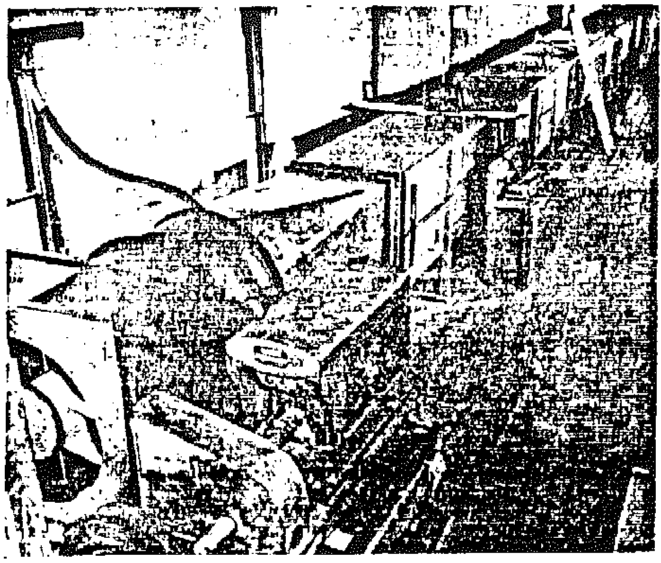

Fig. 1 (*Left*) View of wind tunnel • Fig. 2 (*Right*) Equipment used for velocity determinations

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The authors: A. W. ZINGG and W. S. CHEPIL, respectively, project supervisor (research), Soil Conservation Service, USDA, and professor of soils, Kansas State College, Manhattan.

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●Numbers in parentheses refer to the appended references.

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organic matter, lime, and alkali salts content, and possibly other soil charactertistics on the detachability of soil by wind.

4 To evaluate the effects of plant covers and residues, surface barriers, various topographic features, the degree and nature of the surface roughness, and various mechanical and land-use practices on soil drifting.

5 To delineate principles upon which the design of control practices can be based.

The first year was devoted primarily to development. By the end of 1948, a laboratory and a field wind tunnel had been constructed and subjected to preliminary tests. A laboratory for carrying out certain physico-chemical analyses of soils subject to wind erosion was also equipped. Studies of the physical and chemical properties of soils as related to wind erodibility have already yielded valuable information.

The Soil-Blowing Tunnel. The consensus of those who have worked with wind erosion investigations is that most problems of a fundamental nature may best be studied with an artificial air stream since variables common to the problem may be better controlled in a wind tunnel than in the open. Tunnels of various types and sizes have been devised by workers in this field. Bagnold(1) of England studied the physics of wind-blown sands and desert dunes with a suction-type laboratory tunnel having a 1-ft square cross section and a length of 30 ft. Chepil(13) of Canada employed a circulating-type laboratory tunnel having a rectangular working section 2½ ft in width by 2 ft in height and a length of 13 ft; also a portable field tunnel with a cross section 3 ft wide and 3½ ft high, wherein the length was varied from 32 to 48 ft. Malina(11) of California developed a laboratory tunnel of the suction type with a working section 2½ ft wide by 1½ ft in depth. Its length was 12 ft. Again, a portable tunnel for field use was constructed by Joy(6) in South Dakota. The dimensions of the tunnel were 3½ ft wide by 3 ft in height by 48 ft long. Schoenleber(12) of Kansas constructed and made preliminary tests on a field tunnel with a square section of 4 ft and a length of 39.4 ft. More recently, Kucinski(9) of Massachusetts constructed a laboratory tunnel 3 ft square with a working section 16 ft long.

From the above, it is apparent that the type and dimensions of the wind tunnels used to study erosion have varied greatly. Unavailable for all tunnels is a comprehensive description of the characteristics of the air stream throughout the length of the working section. In general, the laboratory-type tunnels have been of the suction or circulating type. Those designed for use in the field have employed a propeller to force the air stream through the duct. Only very elementary straightening vanes have been used on the latter and their aerodynamic characteristics are largely unknown.

In developing the present wind tunnel at Kansas State College the plan has been to construct one of a type and dimension suitable for use either in the laboratory or in the field. Flexibility which will permit optional conversion between the forced air, suction, or circulating types has been maintained. Thus, in effect, the field-type tunnel has been brought into the laboratory for development. The cross section of the present duct is 3 ft square, and its length is 56 ft. The building which houses the tunnel is 92 ft long.

A photograph of the tunnel and air-moving equipment is shown in Fig. 1. The wind-making equipment is comprised of a governor-controlled gasoline engine and a heavy-duty axial-type ventilating fan. Both are assembled as a portable trailer unit. Control of air movement is effected partly by changing the speed of the engine and also by an adjustable-vane inlet not shown in the photograph. For normal operating ranges the engine is run at a constant speed and control is obtained with the adjustable air-intake device. The air flow from the fan blades is redistributed and evened out by a series of screens in the metal transition section connecting the fan to the duct. A honeycomb-type air straightener is located in the upper portion of the duct immediately below this transition section. It is fabricated from 324 two-inch aluminum tubes, each 1 ft in length.

The 56-ft length of the tunnel was made by joining together seven separate sections, each 8 ft in length. The sides of the duct are comprised of alternate plywood and plate glass panels. The alternate wooden panels are removable to give easy access to the test space. Removable also is the top of the duct which is made from ¾-in plywood. In addition, the top panels slide along the horizontal length of the duct to provide ingress for air measuring and other devices at desired points. Air flowing from the end of the tunnel discharges into a dust-collecting room, with a floor area of 300 sq ft and a height of 13 ft. It is then discharged outside through doors or through ports in the ceiling to the second floor of the building, where it may be recirculated to the fan. In the arrangement shown in Fig. 1, the air-moving unit pushes the wind stream through the tunnel. By placing this unit in the room beyond the far end of the duct, a suction-type tunnel is obtained.

Soil trays of a 18-in width are to be installed in the center of the 3-ft tunnel width. During operation, changes in soil weight throughout the length will be recorded on scales below. To be installed also are scales to determine the shearing or tractive force of the air stream on the soil surface.

An aluminum duct will be used with the portable air-moving unit in the field. It is comprised of collapsible sections 6 ft in length. Should the arrangement prove practical, it will be used to determine drifting characteristics of soils in their natural state.

A six-tube multiple manometer has been constructed for use in determining velocities of air movement in the tunnel or in the field. The slope of the tubes magnifies changes in liquid elevation 20 times. Alcohol is used to give the sensitivity desired. A movable staff holding 6 pitot tubes is used to make velocity traverses throughout the tunnel. A close-up view of the apparatus is given in Fig. 2.

A typical distribution of air flow common to the tunnel is shown in Fig. 3(A). Plotted isovels are those for a cross section located 48 ft to leeward of the honeycomb straightener. In this instance the floor was covered with non-erosive gravel ranging in diameter from ⅛ to ¼ in. To obtain the favorable distribution of the air stream shown, it was necessary to even out irregular delivery characteristics of the fan with a series of screens. The utilization of a precisely made straightening device to remove both vertical and horizontal components of rotational flow was also essential. Incidentally, approximately one-third of the fan velocity pressure was sacrificed to accomplish this end. It is apparent that a suction-type tunnel would be more efficient. Problems connected with pulling eroded materials through the fan may, however, offset this advantage.

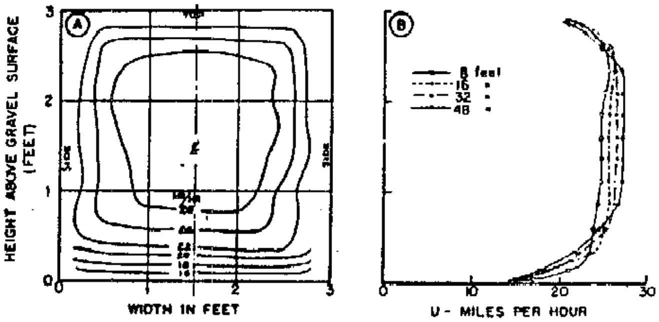

Fig. 3 (A) Velocity distribution at a point 48 ft downwind in tunnel. (B) Profiles of flow at center line of duct at horizontal distances of 8, 16, 32 and 48 ft downwind in tunnel

Profiles of air flow along the vertical center line of the tunnel are given in Fig. 3(B). Points of inflection in the curves indicate that the turbulent boundary layer attains a height of approximately 2 in above the gravel surface in a distance of 8 ft. It develops progressively to a height of 10½ in at a location 48 ft down the duct. Growth of the boundary layer is proportional to the four-fifths power of the tunnel length. To satisfy the law of continuity, the flow in the central portions of the tunnel must therefore, increase in the uniform cross section used. It is believed that all the duct, excepting possibly the first 16 ft, has conditions of air flow suitable for test purposes. Extrapolation of the length-boundary layer growth relationship indicates that a duct length in excess of 100 ft would be required for the boundary layer to develop throughout the central regions of the tunnel.

Description of Wind Movement. Atmospheric surface winds are turbulent for all velocities in excess of approximately 2 mph. Turbulence of the wind in the open is indicated by the irregular velocity fluctuations known as gusts. Technically, the wind movement in which we are interested from a soil erosion standpoint may be described as a turbulent boundary layer above an aerodynamically rough surface.

A "rough" surface is one in which separation of the flow occurs from the macroroughness of which it is comprised. The low intensity of the pressure in the wake of the roughness leads to resultant forces which oppose the motion. Such forces are customarily termed "form drag."

An expression to describe fluid flow of this type in round pipes has been developed by von Karman(8) as follows:

$$\frac{\mu}{\sqrt{\frac{\tau}{\rho}}} = \frac{1}{K_0} \, ln \, \frac{z}{K} + C \text{ .... [1]}$$

where μ = the average velocity of the fluid at a distance z normal to a pipe wall; the expression $\sqrt{\frac{\tau}{\rho}}$ is termed the friction velocity, where τ is the intensity of the shearing force per unit area at the pipe wall, and ρ is the density of the fluid; K_0 is a dimensionless constant usually associated with a characteristic turbulent mixing length; K is the linear height of the surface roughness, and C is a constant. Prandtl(2) has suggested that equation [1] could be extended to the atmosphere.

Comprehensive experiments in round pipes were carried out by Nikuradse(14) to determine the constants for equation [1]. This was accomplished by cementing sand grains of various sizes to the pipe wall. A value of $K_0 = 0.4$ and of $C = 8.5$ was found to satisfy the relationship. Substituting these values of K_0 and C in equation [1] and converting to the logarithmic base 10 yields the expression

$$\frac{\mu}{\sqrt{\frac{\tau}{\rho}}} = 5.75 \log. \frac{z}{K} + 8.5$$

A value of $K/30$, designated as k, will satisfy the above expression and eliminate the constant $C = 8.5$, which after transposition becomes

$$\mu = 5.75 \sqrt{\frac{\tau}{\sigma}} \, \log \frac{z}{k} \text{ .... [2]}$$

This basic equation with several modifications has been used by Bagnold to describe the variables common to sand movement by wind both in the wind tunnel and the open field. Chepil has likewise applied it to an analysis of soil drifting by wind.

Application of equation [2] has proved a very useful tool in clarifying the wind erosion phenomenon. The relationship has, however, been developed for pipes in which the linear dimension of the roughness has been superimposed on the pipe wall. The base for measurement of z was a specific surface which does not exist for surfaces in the field. Further, the value of K is a linear dimension of roughness only. Land surfaces in the field have roughness varying in height, spacing, porosity, angularity, etc. Because of these differences, difficulty is encountered in applying the expression. An illustration of such experience will be given.

A series of wind velocity measurements was made over a cultivated stubble on the Agronomy Farm near Manhattan on October 15, 1948. Irregularties of the surface varied from 3 to 6 in vertically. Velocity measurements of the atmospheric wind were obtained simultaneously at each of 5 elevations. Pitot tubes and a multiple manometer were used for this purpose. Fifty sets of readings were obtained at approximate 10-sec intervals.

To fit the data obtained into equation [2], it was necessary to orient the elevations at which readings were secured to a height comparable to the z defined therein. The average velocity should plot as a function of the logarithm of z when this is accomplished. The steps followed in doing this were as follows:

1 Leveling of the irregularities of the surface, above which readings were taken, to determine its average elevation.

2 Determining by trial and error the adjustment required from the average elevation of the surface to make the semilogarithmic plot project as a straight line to an average zero velocity at a finite height (k).

In this particular instance it was found that the height z must be measured from an elevation 1½ in below the average elevation of the surface to produce the desired velocity-log height relationship. A plot of the individual velocity readings obtained at heights determined by the above orientation is shown in Fig. 4(A). A line representing the average of the readings is presented in Fig. 4(B). It will be noted that the value of k, or the height at which an average zero velocity, is, in this instance, one inch above the datum for measurement of z. If the value, $k = 1$ in, is interpreted in the light of its meaning according to the equations and experiments from which it was derived, the linear height of roughness is found to be equivalent to 30 in. This is not reasonable. In other words, the state of the surface and velocity distribution over it apparently vary widely from the original experiments in pipes.

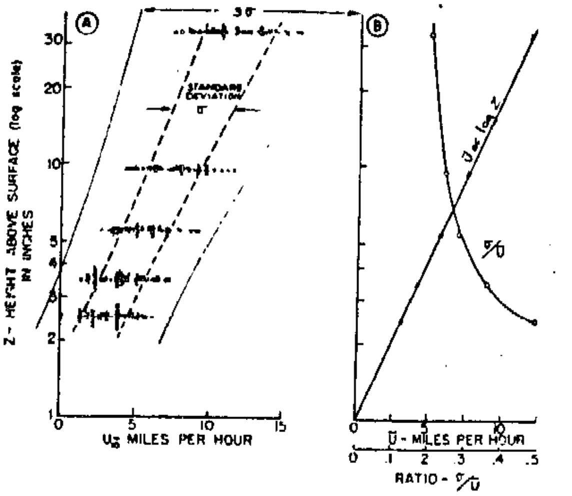

Fig. 4 (A) Values of wind velocity at various heights secured at 10-sec intervals in the open over a rough cultivated stubble. (B) Showing relationship obtained for an average of the velocities at each height, also the ratio of the standard deviation to the average velocity at each height

The above difficulties and uncertainties involved in applying equation [2] have been encountered likewise in preliminary experiments with surfaces of varying roughness in the laboratory tunnel. At present, efforts are being made to develop basic formulas which may be applied more easily. Attempts are also being made to derive a parameter to define better the aerodynamic roughness of various land surfaces.

In investigations of sediment transportation a clarification of factors governing bed-load movement recently has been obtained. This has been accomplished by considering the value of velocity fluctuations and associated forces in initiating movement of particles. These principles have not been applied to the initiation of movement of soil by wind; however, the approach as outlined by Kalinske(7) appears to offer possibilities. The range of the standard deviation, σ, of the velocity measurements presented is given in Fig. 4(A). Shown also is the value of 3σ or the limit of 99.7 per cent of the occurrences, provided the velocity fluctuations follow the normal error law. In this instance, it is to be noted that the average velocity at a 2½-in height (near the maximum projections of the surface) is approximately 3 mph. The limit of 3σ is 7½ mph. Assuming that the shear on particles at this point on the surface is proportional to the square of the velocity, the tractive force for maximum velocity fluctuations would be over 5 times the value common to the average velocity.

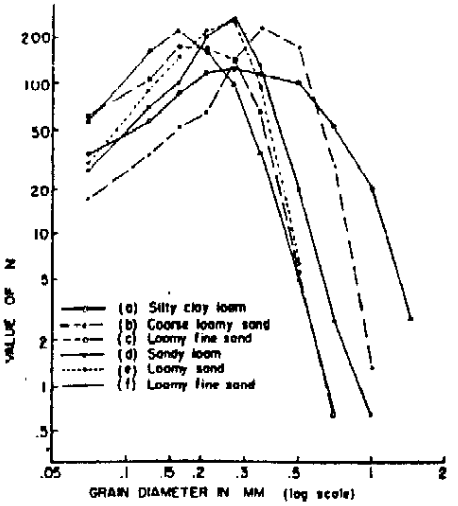

Fig. 5 Size distribution of soil grains found in newly formed drifts in the spring of 1948

The ratio of the standard deviation to the average velocity, σ/U, is plotted for various heights in Fig. 4(B). This factor is associated with the relative intensity of gusts. Thorough investigation of the value of this ratio should be made for wind movement in the field. A common statement encountered in the plains is "Some winds move soil while others that blow just as hard do not." The relative magnitude of gusts could well have a bearing on the subject.

Movement of Soil by Wind. The movement of soil by wind is a complex process influenced by innumerable conditions of wind, soil, and nature of the eroding surface. The effects of some of these conditions have been studied by various investigators. Much more information will be necessary, however, before the wind erosion process can be understood and described thoroughly. Likewise, more information is needed to evaluate the effects of various cultural treatments and control practices on the drifting of soil by wind.

The soil is moved by wind in three types of movement—saltation, suspension, and surface creep. Accurate measurement of each type of movement, particularly of suspension, is difficult. Attention is being given at present to devising more accurate methods of measurement than have been used formerly.

In addition to the variations in the types of soil movement, the wind erosion phenomenon is further complicated by close interdependence of at least five forms of erosion. Chepil(3) has recognized these forms, although all can well be considered as different phases of the same phenomenon. These forms described are effluxion, extrusion, detrusion, efflation, and abrasion. Some, or all, of these forms may be operating at the same time. However, none of the forms can exist without effluxion, which consists primarily of the removal by wind pressure of the grains moving in saltation. Effluxion is, in other words, a prerequisite to, and a cause of, the other forms of erosion. This form of erosion involves the movement of a relatively narrow size range of soil particles, usually within 0.05 to 0.5 mm in diameter. The whole program of wind erosion prevention and control should, therefore, be based on either reducing the amount of this size of particle in a soil to an allowable minimum, or protecting it from the erosive force of the wind. Investigations are being conducted to determine this minimum for various soil types, surfaces, and wind velocities. Experiments have also been undertaken to find out how best to alter the size of soil aggregates so they will offer the greatest resistance to erosion by wind and, at the same time, preserve a favorable condition for growth of crops.

Investigations are being made of the intricate phenomenon of the sorting of soil material by the wind and its relationship to possible changes in the productivity of agricultural land. Fig. 5 gives some information on the size distribution of soil material blown about and deposited by wind to form drifts or small dunes on several soils in Kansas in May, 1948. The grading patterns shown in this figure were obtained by plotting the logarithm of the percentage weight of soil per unit of the log-diameter scale against the logarithm of grain diameter. Assuming the diameter limits of each fraction as determined by sieving to be d_1 and d_2, the logarithmic interval of grain diameter is given by $\log d_1/d_2$. The percentage weight P of each grade per unit of log-diameter scale is then equal to ΔP divided by $\Delta \log d_1/d_2$, which is designated by N. For a given soil material, it will be seen that there is a predominant diameter drifted by wind and that the fractions larger and smaller than this diameter fall off at a more or less constant rate. It is apparent that the sizes to the right and the left of the predominant diameter grade off independently of each other. The predominant diameter of the soil material deposited into dunes from 6 different fields is shown to range from 0.16 mm to 0.35 mm and averages 0.25 mm. These values correspond closely to the size of soil particles forming dune materials in Western Canada(4). There it was found that the predominant diameter of particles in drifts, excluding those from lacustrine clay not represented in the Kansas tests, was likewise 0.25 mm. The predominant diameter of the particles in drifts coincides in some cases fairly closely with their average diameter, but in other cases it is at wide variance with the average diameter.

It should be noted that the material moved about and deposited into dunes by wind constitutes only a part, though a major part, of the total movement. Fine dust, once lifted into the air, is carried great distances away from the eroded area and is deposited on the earth's surface only with rain or after velocity of the wind has slackened considerably. The removal of fine particles from the soil is usually minor in comparison to the rate of movement along the surface of the ground. In some cases, however, it constitutes a much more serious aspect of the wind erosion problem. The wind acts on the soil as a fanning mill on grain, removing fine silt and clay fractions and leaving sand and gravel behind. This sorting action, continued for many years, tends to make the soil coarser in texture, and consequently more erodible, and perhaps less productive, than they were originally.

A typical case illustrating the aspects of the sorting action by a single wind storm occurring in 1948 is shown in Fig. 6. It shows the structure of the soil material moved about and deposited into small dunes in relation to the structure of the residual soil. The drift material contains a very small quantity of particles averaging 0.016 mm and not exceeding 0.05 mm in diameter. The residual soil, or that soil from which the drift material was derived, is shown to contain more than five times the proportion of these fine particles. This indicates that most of these particles in that portion of the soil affected by the wind have been removed from the eroding area. It may be expected that soils containing appreciable quantities of sand will become a little more sandy with each succeeding wind storm, unless the geologic processes of silt and clay formation

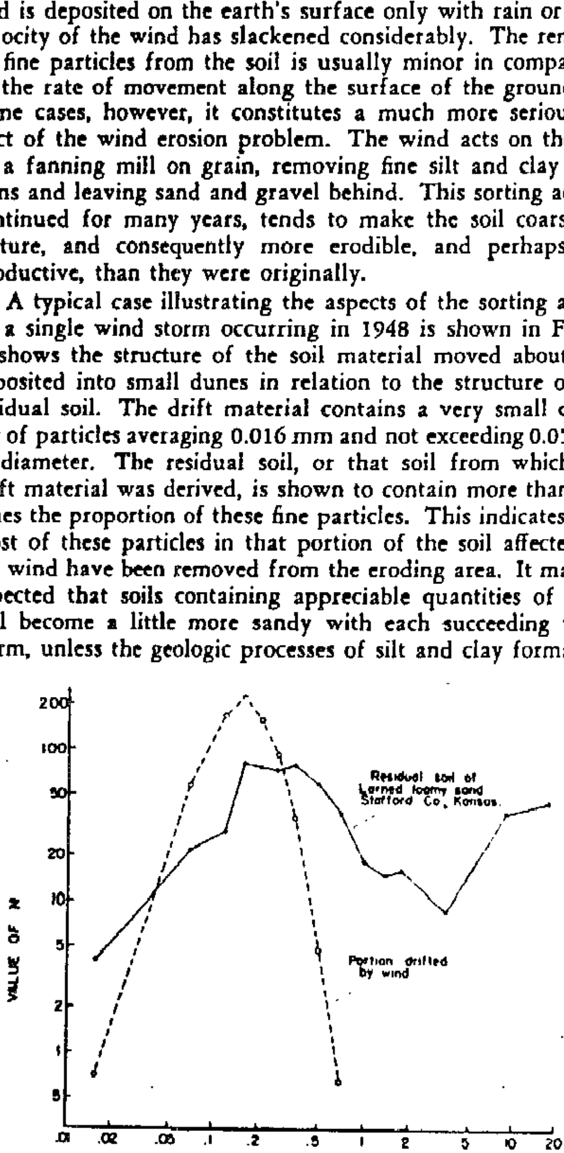

Fig. 6 Dry aggregate composition of a cultivated soil and materials drifted therefrom

proceed at a rate equal to, or greater than the rate of removal. It is evident, however, that an annual rate of removal, based on only a single dust storm such as the one shown in Fig. 6, is much greater than the geologic rate of accumulation.

The data in Figs. 5 and 6 also indicate the maximum size of soil grains moved by wind. No quartz fractions greater than 1 mm and only small proportions of sand coarser than 0.5 mm in diameter were found in the drift materials, indicating that erodible quartz grains seldom exceed 0.5 mm in diameter Soil grains having a high degree of porosity, such as those represented by Fig. 5(A), are moved more readily by the wind. Even for this type of soil material, not over 5 per cent exceed 1 mm in diameter.

SUMMARY

The basic nature of problems common to the dynamic action of fluids on the land surface is cited. Studies of the phenomenon of soil erosion by wind initiated at the Manhattan, Kansas, headquarters are outlined briefly.

Experiences with the soil-blowing tunnel are discussed. Some of the aerodynamic characteristics of the tunnel developed at the Manhattan laboratory are given.

Formulas which have been applied to the description of surface wind movement are presented. Demonstrated, also, are problems common to the application of these relationships to the phenomenon of wind movement above field surfaces.

The types of soil movement and forms of erosion caused by wind are summarized, and some of the physical characteristics of several soil materials blown about and drifted into small dunes in the spring of 1948 are presented.

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