WIND-TUNNEL STUDIES OF THE MOVEMENT OF SEDIMENTARY MATERIAL

By

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Knowledge of the characteristics of sand and soil movement by wind is basic to the design of measures to cope with the wind erosion problem. The need for the scientific approach tends to become greater with the passing of time and the increasing need to control and utilize our resources to the fullest.

Studies of the movement of sedimentary materials by wind have been quite limited in comparison to those using water as the fluid medium. Bagnold [1, 2] has made comprehensive studies of the movement of sand by wind. Also, Chepil [3, 4, 5] has reported on the movement characteristics of soil granules. A review paper on the subject has been published by Malina [6]. Differences in the nature of particle movement in air and water have been discussed by Kalinske [7]. His analysis leads to the conclusion that the height of bounce of sand grains in water will be about 1/800 of that in air for equal values of shear. In 1947, von Kármán [8] published a speculative evaluation of the phenomenon of surface ripples in wind. The rotation characteristics of sand grains as they are moved in the saltation process by wind have been clarified through high speed photographic studies and reported by Zingg [9].

The research presented here is largely exploratory and has been in progress only a short time. The development of equipment and experimental techniques suitable for the study of movement of sedimentary materials by wind constitutes a problem of considerable proportions. Any deficiencies will be reflected in experimental data. No attempt has been made to make a dimensionless presentation of experimental results. The data presented are a portion of those contained in a master's thesis by the author [10]. Acknowledgement is made to N. P. Woodruff of the project staff for his assistance in carrying out the research.

EXPERIMENTAL EQUIPMENT

A laboratory wind tunnel was employed to provide an air stream for the study of moving sand. Briefly, the wind-making equipment comprises a governor-controlled gasoline engine and a heavy-duty axial-flow type ventilating fan. Control of air movement is effected partly by changing the speed of the engine and partly by an adjustable vane inlet. 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 a 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. The duct of the tunnel is 56 feet long and 3 feet square. The tunnel and characteristics of velocity distribution developed throughout the length of the duct have been described previously [11].

A special Pitot tube was constructed to measure wind velocities above sand surfaces in the tunnel duct. The impact portion of the tube was a hypodermic needle with a 0.5 mm. inside diameter. Control of height for traverses above sand surfaces was accomplished by clamping the vertical brass tubing to a graduated vernier-type point gage.

An alcohol manometer inclined at a 1:20 slope was used to register air-velocity pressures. This manometer was constructed in the laboratory for general use. It was calibrated by use of a Dwyer hook gage employing an air stream to develop velocity pressures. Values of wind velocity obtained are for standard temperature and atmospheric pressure conditions; i.e., 70°F. at sea level.

One of the variables in sand movement by wind is the value of τ_0, the average shear or drag of the wind on the surface. Its indirect determination from velocity traverse is often difficult or problematic. As an aid in determining its true value for a given condition, equipment was constructed to measure it directly. A 4-inch layer of 2-6 mm. gravel comprised the "floor" of the tunnel. A metal tank 18 inches wide and 8 feet long was recessed into this bed of nonerodible gravel. A smaller tank to be placed inside the other with approximately $\frac{3}{8}$-inch clearance on the sides and $\frac{3}{4}$-inch clearance on the ends was also constructed. This second tank was 3 inches in depth. Its surface area was 11.5 square feet. Water was used to float the smaller tank. It was partially filled with insulating board to give it buoyancy sufficient to carry a layer of experimental sand. When properly weighted the floating tank formed a "shear tray", simulating an integral portion of the bed. The horizontal drag of the wind on the tray was transmitted to a small spring scale placed outside the tunnel by use of thread passing over fiber pulleys. The scale registered the value of τ_0 in grams.

Equipment to collect quantitative samples of airborne sediment at four heights was developed. The device was designed for use either in the laboratory or field. The sampler has been described in a previous publication [12]. Briefly, the average velocity of intake of the 0.92-inch square sampling tubes is controlled to equal the velocity of the sediment-laden air stream at the level of sampling. Separation of sediment is made by a system of filters.

PROCEDURE

Several cubic feet of sand of varying size were obtained by dry sieving a water-deposited sand collected near the Arkansas River in south-central Kansas. The sands are predominantly quartz. The grains tend to be smooth, well rounded, and approximately spherical in shape. The five size separations obtained are shown in Table I.

TABLE I

SCREEN SEPARATION SIZE RANGES AND AVERAGE DIAMETERS OF SAND, IN MM.

Screen separation	Average size
0.15-0.25	0.20
0.25-0.30	0.275
0.30-0.42	0.36
0.42-0.59	0.505
0.59-0.84	0.715

The sands were placed on trays 18 inches wide along the center line of the bottom of the tunnel. The horizontal length of exposed sand varied from 16 feet for the smallest to 32 feet for the largest size used. The lower 8 feet of the exposed sand area was contained on the shear-measuring device. Wind velocities above a point near the center of the shear tray were obtained by use of the small pitot tube described previously. Sand passing the lower end of the shear tray was sampled by use of the increment sampler.

Tests were first made on each of the graded-sand surfaces after they had been stabilized to drifting from wind action by use of a fine water spray. Velocity traverses were made over each stabilized sand surface for five levels of wind movement. The base of height measurements was the average center elevation of the grains comprising the bed surface. An arbitrary total pressure measured in the transition section between the fan and the duct provided an index for the systematic variation in the level of wind movement. The location of this arbitrary pressure, designated P_1, and its relation to velocity and bed shear has been described and published previously [13]. Direct measurement of the horizontal shear on the bed was obtained for each level of wind applied.

The sands were next studied in a dry state by subjecting them to several intensities of shear wherein movement occurred over the entire bed. The surface was permitted to erode for a time of two minutes. During this time a velocity traverse was made over the moving bed above the shear tray. The four-increment sampler was operated during each two-minute period to determine the quantitative distribution of moving particles with height.

Four observers were required to operate the tunnel and obtain experimental data over the moving sand surfaces. The first operated the wind tunnel and controlled the level of wind movement. The second made a velocity traverse of the sand-laden air stream. The third read and recorded velocities during the traverse above the bed and the drag indicated by the dial of the shear-measuring scale. The fourth was required to control the air intake of the sand sampler.

Insofar as possible the experiment was carried out on a routine basis. After each two-minute test period the sand bed was leveled, the shear tray re-oriented, and the average bed elevation determined for a subsequent test and velocity traverse. The sand collected by the sampler was removed and weighed after each test.

Data relative to the height and spacing of surface ripples formed at various levels of τ_0 were determined [10]. Because of space limitations, these results are not included in the present paper.

EXPERIMENTAL RESULTS

Velocity Distribution and Shear Over Stable Sand Surfaces

As presented by Rouse [14], the steady and uniform flow of fluids over rough surfaces is approximated by the general equation

$$\bar{u} = C \log \frac{y}{y_1}$$

in which $\bar{u}$ is the velocity at any height y, and y_1 is a reference parameter equal to the value of y at which the curve intersects the y-axis.

The coefficient C represents the slope of the curve and, according to von Kármán's development [15], is equal to $\frac{2.3}{k}\sqrt{\frac{\tau_0}{\rho}}$, in which the term $\sqrt{\frac{\tau_0}{\rho}}$ is the velocity gradient or friction velocity, τ_0 is the average surface drag of the wind per unit area of surface, ρ is the mass density of the fluid, and k is the universal constant for turbulent flow. Experiments by Nikuradse [16] have shown the value of k to be 0.40 for clear fluids.

The roughness elements of the surface have been found by Gold-

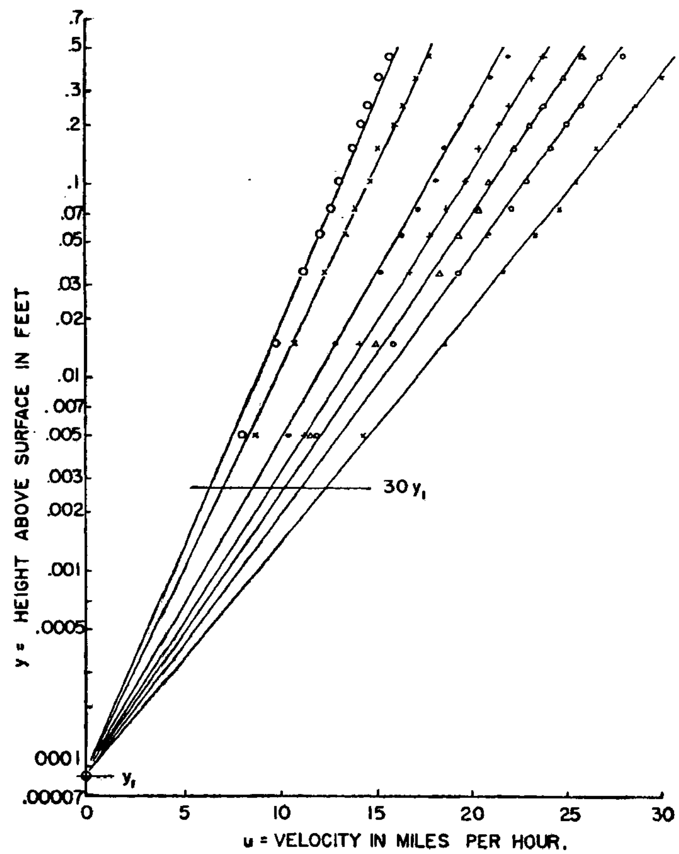

FIG. 1. RELATIONSHIP OF WIND VELOCITY TO HEIGHT ABOVE A 0.30-0.42 MM. STABILIZED SAND SURFACE WITHIN THE TURBULENT BOUNDARY LAYER.

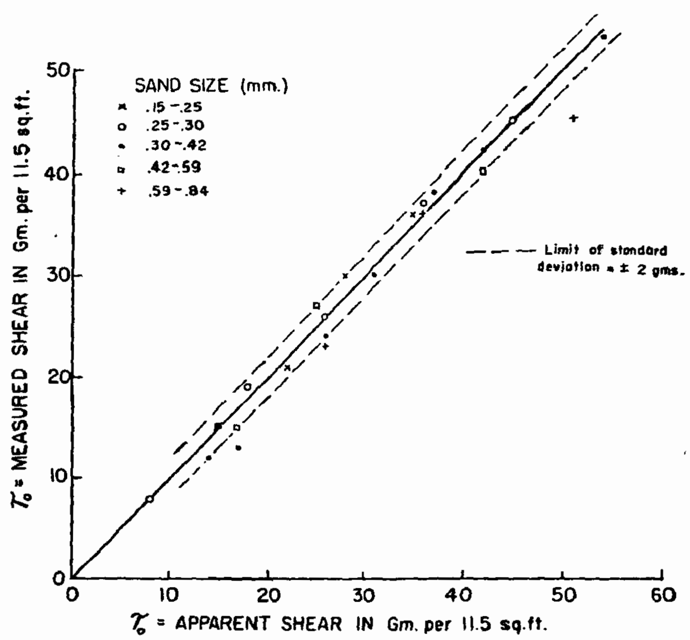

FIG. 2. COMPARISON OF APPARENT AND MEASURED SHEAR VALUES OBTAINED FROM STABILIZED SAND SURFACES OF DIFFERENT RANGES OF SAND.

stein [17] and White [18] to be within a laminar sublayer if the Reynolds number of the boundary layer,

$$R = \frac{d\sqrt{\tau_0/\rho}}{\nu}$$

is less than a critical value of 3.5 or 4. In this expression, d is the grain diameter and ν is the kinematic viscosity of the fluid. If the critical value of R is exceeded, the laminar layer is disrupted completely and the rough-boundary equation appears to hold, within the region of the roughness elements comprised by the surface.

The present research considers only flow and surface conditions above the critical value of R. The experimental results provide an opportunity to check all factors in the rough-boundary equation for surface roughness composed of several size-ranges of sand.

A sample plotting of the distribution of velocity over the 0.30-0.4 mm. sand surface is given in Fig. 1. The family of lines draw through the points indicating the variation of velocity with heigh for varying average wind velocities is shown to converge to a va ue of y_1 equal to 0.00009 feet, or 0.0274 mm. The apparent shearin force on the surface is calculable from the von Kármán equation by its use in the form

$$\bar{u} = 5.75 \sqrt{\tau_0/\rho} \log (y/y_1)$$

If for $y = 30y_1$, $\bar{u} = \bar{u}''$, the equation becomes

$$\bar{u}'' = 8.5 \sqrt{\tau_0/\rho} \text{ or } \tau_0 = C_1(\bar{u}'')^2$$

The surface drag τ_0 was read in units of grams per 11.5 square feet of area of the shear-measuring device and velocities were recorded in miles per hour for the experiment. To determine the apparent shear for these dimensional units

$$\tau_0 = 0.362(\bar{u}'')^2$$

The agreement between measured and calculated shear provides a check on the validity of the use of the value $k = 0.40$ in the von Kármán equation. This agreement is shown graphically in Fig. 2. Calculated and measured shear are equal for an average of the data. The standard deviation between them is $\pm$ 2 grams. The standard error or the range within which the true value lies is τ_0(meas.) $= \tau_0$(calc.) $\pm$ 0.41 grams.

It has been assumed by Bagnold [2] that the value of y_1 is approximately equal to 1/30 the diameter of sand grains on the bed. White [18], however, has obtained values of approximately 1/9. The results given in Table II were obtained in the present experiment.

TABLE II

VALUES OF y_1 AND $\frac{d}{y_1}$ FOR VARIOUS SIZES OF SAND

Average diameter of sand (d) (mm)	Value of y_1 (mm)	Ratio $\frac{d}{y_1}$
0.20	0.0046	43.5
.275	.0137	20.1
.36	.0274	13.1
.505	.0366	13.8
.715	.0487	14.7

A plotting of the above data is shown in Fig. 3. The value of y_1 apparently varies as the log of grain diameter. An average relationship is

$$y_1 = 0.081 \log \frac{d}{0.18}$$

The fact that $\frac{d}{y_1}$ decreases rapidly with grain sizes above 0.2 mm

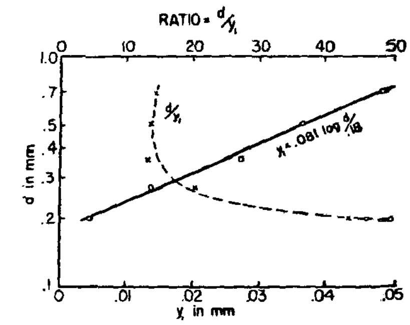

FIG. 3. RELATIONSHIP OF y_1 AND d/y_1 TO AVERAGE GRAIN DIAMETER d.

may account for the variable results obtained by various investigators. A reversal from a minimum value of approximately 14 is shown to take place as the grain diameter increases beyond 0.5 mm.

Velocity Distribution and Shear Over Drifting Sand Surfaces

The distribution of wind velocity above a moving bed of sand has been found by Bagnold [2] to be of the type

$$\bar{u} = C \log \frac{y}{y'} + u'$$

where $\bar{u}$ is the velocity at any height y, and y' is the height at which the velocity distribution curves project to a focal point at a velocity u'. As over the stable sand surfaces, C is a coefficient representing the slope of the lines and has been assumed by Bagnold to be equal to $5.75 \sqrt{\tau_0/\rho}$.

From studies of the results of the present experiment, it became apparent early that the velocity distribution curves approximated a curved shape near the bed. This result is at variance with the velocity profiles obtained by Bagnold. From studeis of photographs it was also evident that drifting sand had lateral components of movement and that a considerable portion of it was drifting beyond the 18-inch width of the sand bed. This dispersion and non-uniform distribution of drifting sand across the width of the tunnel duct obviously affected the direct measurements of τ_0 on the 18-inch floating tray at the lower end of the sand bed. A secondary experiment was performed subsequently to clarify the phenomenon. A 16-foot length of the 0.15-0.25 mm sand was placed to occupy the full 36-inch width of the tunnel. Velocity traverses over the drifting sand were made not only in the center but at locations 3 inches from either side of the shear tray. These were averaged for purposes of calculating shear. The procedure was repeated four times, holding the fan pressure constant, making a total of 12 traverses. The sand was leveled before each test and the measured level of shear on the tray was obtained 12 times.

Velocity traverse data from the supplementary experiment are given in Fig. 4. An average velocity distribution curve has been fitted to the data. The average of measured shear values was 24.1 grams per 11.5 square foot area of shear tray. The standard deviation of the measured value was $\pm$ 1.92 grams. Calculating shear from the straight upper portion of the velocity-distribution curve, using a value of $C = 5.75 \sqrt{\tau_0/\rho}$, wherein k, the universal constant, is assumed to be equal to 0.40, yielded an apparent shear value of 27.4 grams per 11.5 square feet area of shear tray. The measured and apparent values of τ_0, therefore, differ significantly. It is appar-

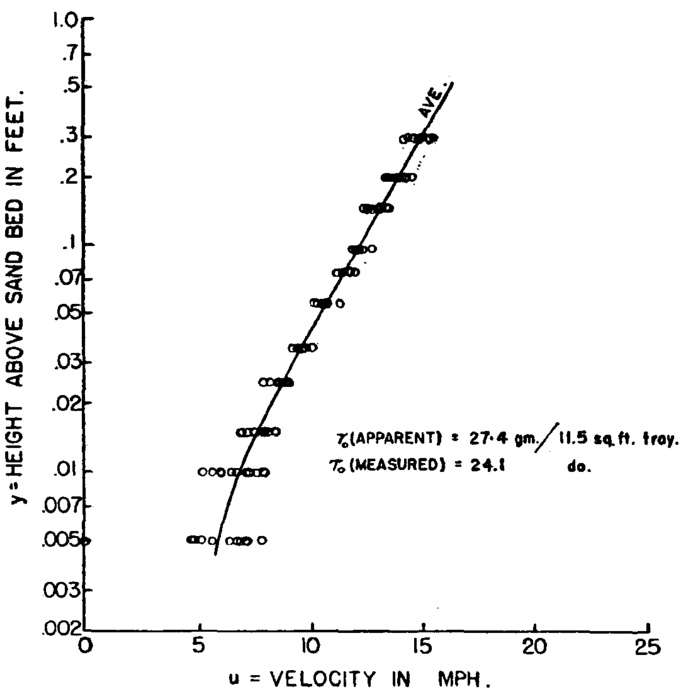

FIG. 4. AVERAGE DISTRIBUTION OF WIND VELOCITY WITH HEIGHT ABOVE A 0.15-0.25 MM DRIFTING SAND SURFACE, SHOWING THE RANGE OF VALUES OBTAINED FOR REPEATED TESTS AT ONE PRESSURE LEVEL OF THE FAN.

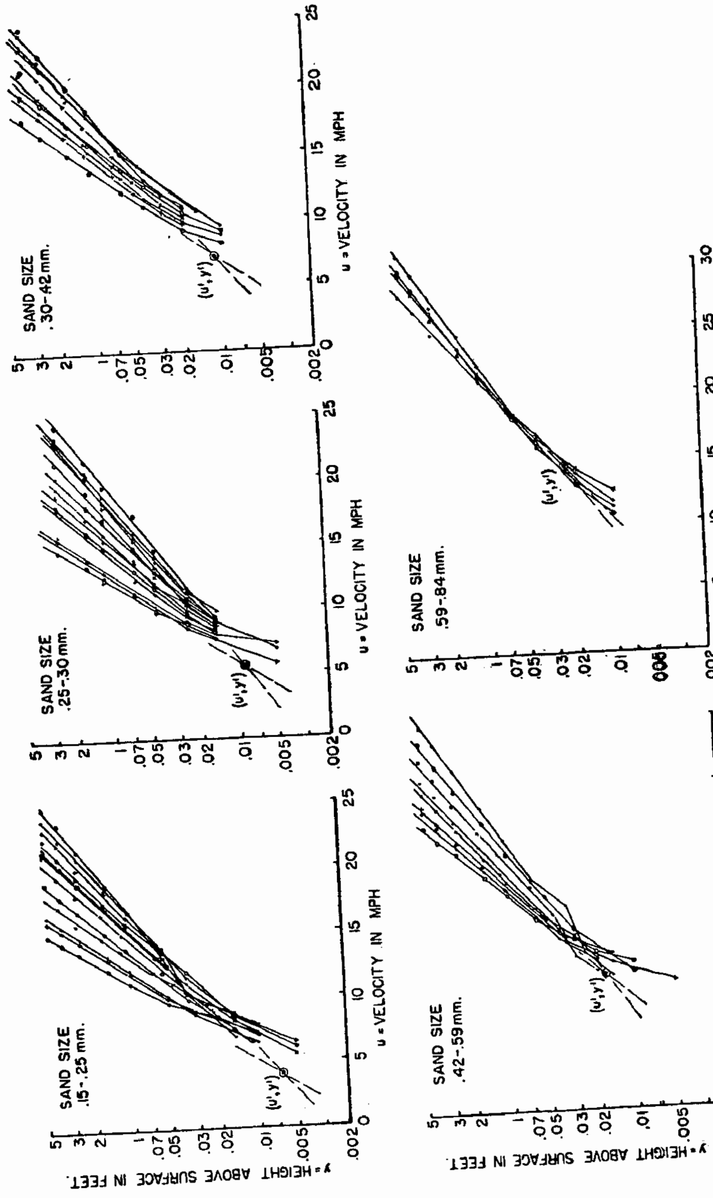

FIG. 5. DISTRIBUTION OF WIND VELOCITY WITH HEIGHT OVER DRIFTING SURFACES OF VARYING GRAIN DIAMETER, SHOWING ESTIMATED VALUES OF THE PROJECTED FOCAL POINT.

ent that a value of $k < 0.40$ is indicated by the results of the experiment. An approximate value of $k = 0.375$ is in close agreement with fact and is used subsequently in calculating apparent shear for the main body of experimental data obtained for sand drifting conditions. Employment of the value of $k = 0.375$ modifies the value of C in the velocity distribution equation to $6.13 \sqrt{\tau_0/\rho}$ and the equation becomes

$$\bar{u} = 6.13 \sqrt{\tau_0/\rho} \log \frac{y}{y'} + u'$$

A plotting of all velocity distribution data from traverses above the surfaces is presented in Fig. 5. The velocity profiles over a given sand for varying wind forces do not follow the straight-line semilogarithmic relationship for values of y below an elevation of approximately 0.05 feet, or 1.5 cm., above the average elevation of the bed. They tend to show a curved convergence, without crossing, to values of y much nearer the bed.

The projected focal point (y', u') appears to bear a relation to grain size. In Fig. 5 it has been located with values of $y' = 10\ d$ and $u' = 20\ d$, y' and the grain diameter d being measured in millimeters, and u' in miles per hour. These values, with the exception of those for the largest size sand, appear to fit the data quite well. The four traverses made on the 0.59 to 0.84 mm. sand are not conclusive in defining a possible "focal point" for the velocity distribution with height. The experimental data are limited to four traverses associated with a limited range of wind force. Additional data were not secured due to the extreme difficulty of maintaining control of elevations of the shear-measuring device with this relatively large size of drifting sand.

The drag measurements for the drifting surfaces were subject to a relatively large error due to the mechanical difficulties involved in floating a tray in the environment of moving sand. It was found that the measured horizontal components of shear averaged 76.7 percent of the values obtained indirectly from the velocity profiles. The coefficient of variation was $\pm$ 11.6 percent. This difference between apparent and measured shear appears reasonable in view of the dispersion of sand flow beyond the 18-inch limit of the bed. A few measurements of the proportion of sand traveling outside the limits of the shear-measuring tray at the end of the bed showed it to be within the range of 15 to 29 percent.

During the process of sand drifting it appears that little of the direct force of the wind is expended on the bed. It appears, rather, that the energy of the wind is transmitted to the entrained sand grains above the approximate elevation of the projected focal point. The sand grains in turn transmit a portion of the energy they have gained from the wind to the bed. The velocity obtained by the grains propelled from the bed to the upper portion of the sand cloud is apparently greater than the velocity of the wind near the bed. As these faster-moving grains descend to the bed they tend to speed up the air moving comparatively slowly near the bed. This appears to be a cause of the superfluity of velocity over the straight-line projection obtained from the relationship existing at greater heights. Again, it is possible that the effective density of the air stream is increased by the entrained sand.

Initiation of Particle Movement

There has been much confusion concerning the average velocity or force required to initiate particle or bed movement of sand. Nearly all graded sands have particles varying somewhat in size, shape, and density. Again, the fluctuations of force on a grain on the bed are statistical and experimental differences are to be expected. Bagnold [2] gives "impact" and "fluid" threshold values for various sizes of sand. His "impact" threshold was obtained by initiating a sustained saltation movement by dropping sand on the bed near the upwind end of a tunnel. The value of adding kinetic energy to the bed to initiate particle movement and to determine a "threshold" value associated with it is not clear. Chepil [4] recognizes the spread of values that may be obtained for visual determinations of "fluid" and "impact" threshold and uses the descriptions minimal and maximal to define various phases of the phenomenon.

In working with the relatively large beds of sand of various size gradations, it was apparent that the movement of particles on or above the bed was a quite variable and unsteady phenomenon if the force approximated that at which bed movement occurred. In an attempt to secure a definable value at which bed movement occurred, the device of determining trend lines of force over stabilized and drifting beds was used. The arbitrary fan pressure P_1 used as an index to tunnel operation was found to be directly proportional to the force τ_0 over given stable or drifting surfaces, as determined for the velocity distribution over the surfaces.

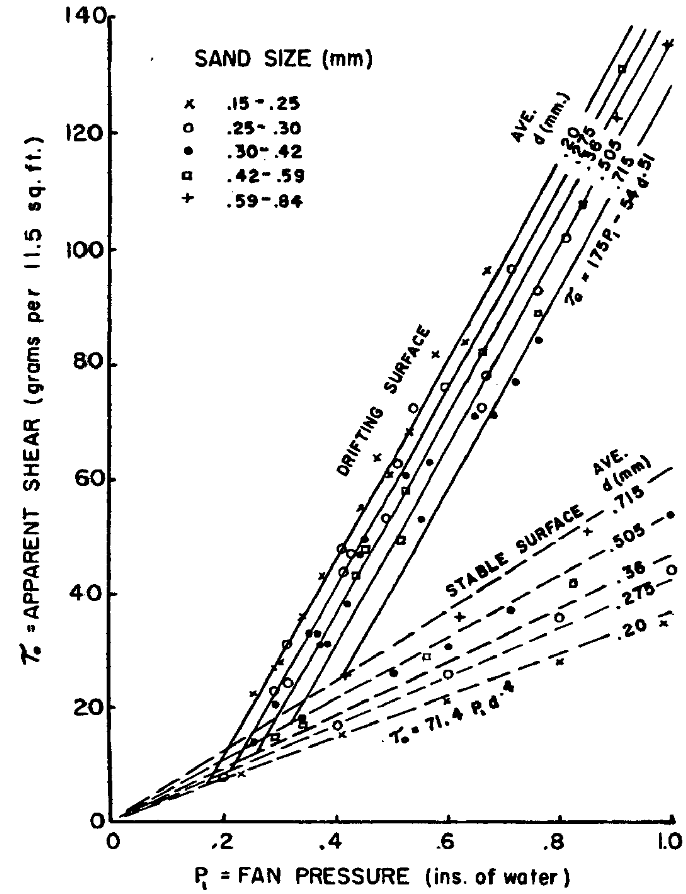

FIG. 6. TRENDS OF APPARENT SHEAR OVER STABLE AND DRIFTING SAND SURFACES IN RELATION TO AN ARBITRARY FAN PRESSURE. THE INTERSECTION OF THE TREND LINES FOR A GIVEN SIZE RANGE OF SAND YIELDS THE SALTATION THRESHOLD SHEAR.

Trend lines giving the relation between P_1 and τ_0 for the varying stable and drifting surfaces are given in Fig. 6. The trend lines were determined by multiple regression procedures employing the method described by Ezekiel [19]. The equation approximating the relation over stable surfaces is

$$\tau_0 = 71.4\ P_1 d^{0.4}$$

in which τ_0 is in grams of force per 11.5 square feet of bed, P_1 is the fan pressure in inches of water, and d is the average diameter of the sand in mm. The index of correlation is $R = 0.917$.

The relation obtained over the drifting surfaces was

$$\tau_0 = 175\ P_1 - 54\ d^{0.51}$$

in which the units of measurement are the same as given for the stable surfaces. The index of correlation was $R = 0.824$.

The point of intersection of the force lines for stable and drifting surfaces appears to represent the best estimate obtainable of a "saltation threshold" for grains of a given diameter. Since it was obtained from force levels for which sustained drifting occurred, it would be somewhat in excess of values for which a few particles drift or roll intermittently on the bed.

Values of the "saltation threshold" determined from the intersection of the force lines of Fig. 6 are shown in Fig. 7. The plotted

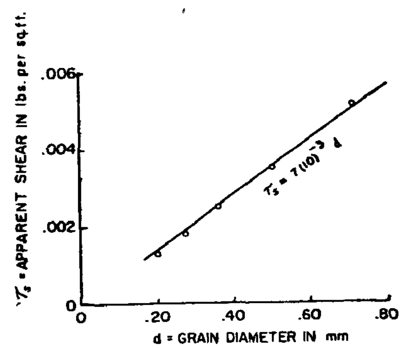

FIG. 7. APPARENT THRESHOLD SHEAR REQUIRED TO INITIATE AND SUSTAIN SAND MOVEMENT FOR A RANGE OF GRAIN DIAMETERS EXCEEDING 0.20 MM.

values are in units of τ_s equivalent to pounds per square foot of bed-area and d in mm. The approximate relationship is

$$\tau_s = 0.007\ d$$

Bagnold [2] and Chepil [4] have used an experimental coefficient in a dimensionless formula to describe a threshold velocity. The expression is

$$u_t = A\sqrt{\beta g d}$$

in which u_t equals the threshold velocity $\sqrt{\tau_0/\rho}$, β is the apparent density ratio $(\sigma\text{-}\rho)/\rho$, ($\sigma$ being the density of grain and ρ the density of air), and A is an experimental coefficient. The value of A was found by Bagnold [2] to be 0.1 for nearly uniform sand grains of diameters > 0.2 mm. Chepil [5] obtained values of A ranging from 0.09 to 0.11 for the "maximal condition." The value of A for the saltation threshold described in the present experiment is 0.116.

Shields' [20] value of α in the expression

$$\alpha = \frac{\tau_0/\rho}{\beta g d}$$

is equivalent to the square of the coefficient A in the formula used by Bagnold. Shields' plot of the dimensionless function α to the Reynolds number of the flow around grains in water gave values of α equal to approximately 0.032 to 0.05 in the turbulent range. A value of $A = 0.1$ is equivalent to $\alpha = 0.01$. For reasons which have not been explained, the values of α found in water are greater than those found in air. A discussion of this subject is given by Bagnold [1].

Distribution of Sand Flow Above the Bed

A plot of the weight of sand collected in a two-minute period by the 0.92-inch square openings of the collection device over the 0.20-mm. sand is shown in Fig. 8. The plottings in the upper half of the

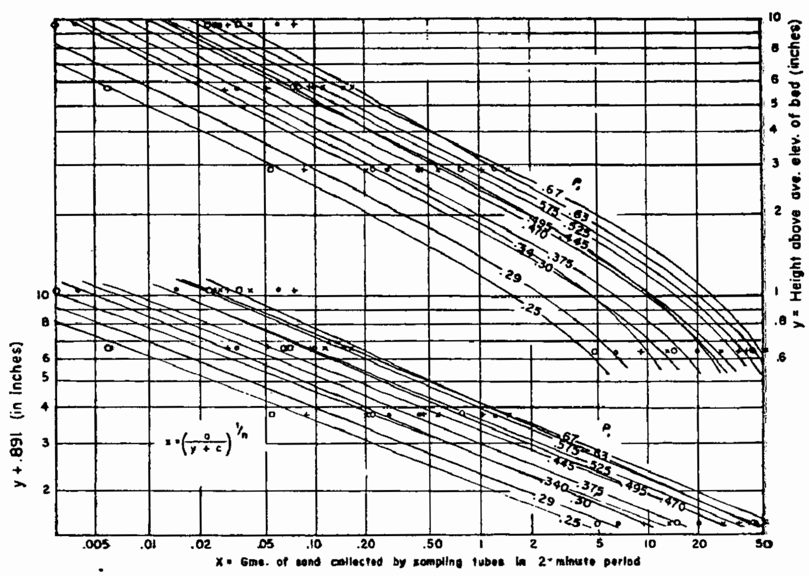

FIG. 8. PLOT OF THE WEIGHT OF SAND COLLECTED BY THE SAMPLER AT FOUR HEIGHTS FOR VARYING PRESSURE LEVELS OF THE FAN.

TABLE III

BASIC DATA FOR DRIFTING SAND SURFACES.

d	P_1	τ_0	n	a	c	q	y_a	Q
0.200	0.25	0.00437	0.243	2.10	0.891	9.2	0.210	97.5
	.30	.00536	.255	2.70	.891	21.6	.229	99.6
	.47	.01225	.265	3.50	.891	52.5	.251	99.0
	.67	.01847	.245	4.15	.891	145.3	.227	97.4
	.34	.00688	.230	2.70	.891	31.5	.211	97.2
	.445	.01056	.240	3.30	.891	63.3	.228	96.0
	.495	.01175	.265	3.50	.891	52.5	.252	99.0
	.525	.01309	.249	3.70	.891	82.5	.222	99.5
	.575	.01577	.259	3.90	.891	85.3	.236	99.6
	.63	.01610	.250	4.20	.891	138.8	.235	97.0
	.375	.00822	.239	2.95	.891	39.0	.216	98.6
	.29	.00519	.238	2.30	.891	14.1	.216	97.5
.275	.425	.00907	.209	4.70	1.80	45.0	.373	97.0
	.55	.01208	.213	5.3	1.80	73.1	.371	97.7
	.715	.01861	.230	6.35	1.80	121.9	.413	97.4
	.81	.02012	.230	7.15	1.80	199.7	.403	99.5
	.29	.00452	.194	3.75	1.80	18.0	.333	98.0
	.41	.00839	.215	4.70	1.80	40.3	.381	97.8
	.485	.01006	.217	5.35	1.80	72.2	.391	99.2
	.66	.01392	.230	6.6	1.80	146.3	.423	96.6
	.76	.01778	.230	7.0	1.80	187.5	.423	96.5
.36	.36	.00638	.391	4.75	.80	45.2	.438	95.7
	.445	.00956	.399	6.07	.80	79.3	.460	95.3
	.55	.01006	.41	6.75	.80	101.3	.462	95.6
	.68	.01359	.398	8.0	.80	161.3	.465	95.2
	.76	.01610	.404	9.3	.80	218.4	.474	95.2
	.72	.01476	.404	8.6	.80	178.1	.464	95.2
	.645	.01376	.393	7.4	.80	138.9	.446	95.2
	.52	.01157	.404	7.1	.80	114.4	.490	93.4
	.44	.00907	.396	5.82	.80	92.8	.463	94.0

figure are for heights y in inches above the average bed level, given on the right-hand vertical scale. These heights of the midpoint of the sample tubes were 0.625, 2.875, 5.625, and 9.625 inches, respectively. Approximate trend lines for 12 levels of P_1 are drawn.

An approximate power function of sand loss with height is

$$x = \left(\frac{a}{y+c}\right)^{1/n}$$

where x = grams of sand collected by the 0.92-inch square sampling tube in two minutes, a is a coefficient of variation, n is the slope of

TABLE III (Cont.)

d	P_1	τ_0	n	a	c	q	y_a	Q
0.505	0.435	0.00839	0.544	6.9	0.512	68.4	0.667	88.5
	.52	.01108	.576	10.8	.512	131.3	.831	86.5
	.66	.01578	.599	14.1	.512	180.0	.912	87.1
	.76	.01712	.631	18.8	.512	248.4	1.181	85.0
	.91	.02517	.599	22.9	.512	403.1	.80	87.8
	.51	.00956	.577	10.2	.512	116.3	.794	87.8
	.59	.01459	.595	12.8	.512	159.4	.996	83.8
	.45	.00922	.547	7.4	.512	76.9	.685	89.8
	.84	.02047	.613	20.5	.512	312.2	1.079	85.6
.715	.85	.01610	.682	24.5	.509	300.0	1.743	80.5
	.985	.02600	.756	37.0	.250	539.1	1.891	75.0
	.78	.01493	.716	20.0	.364	231.6	1.714	78.5
	.905	.02373	.757	32.0	.235	452.8	1.808	75.2

d = Average grain diameter in mm.

P_1 = Arbitrary fan pressure in diffuser section in inches of water.

τ_0 = Average surface drag in lbs. per sq. ft. of bed area, based on a value of $k = 0.375$.

n, a, and c = values in equation $x = \left(\frac{a}{y+c}\right)^{1/n}$ where x = grams of sand collected per 0.92-inch square sampling tube per two-minute period at height y in inches above bed.

q = Rate of sand flow in lbs. per ft. width of bed per hour.

y_a = Average height of sand flow in inches.

Q = Percent of total sand flow carried below a height of 10 y_a.

the sand loss-height function, y the height in inches above the bed, and c a constant. The value of c required to satisfy the above equation was obtained by use of residual equations as described by Lipka [21]. A value of $c = 0.891$ inch satisfies the equation approximately for the 0.20 mm sand. A plot of values of x at $y + 0.891$ is shown in the lower half of Fig. 8. It will be noted that a poor fit of the lines is obtained at the level $y + c = 10.52$ inches. Due to the expanded nature of the scale this involves little error upon subsequent integration of the function. It is of interest that the slope is variable for different values of P_1. This demonstrates that as the flow of sand increases a greater proportion of it is carried at given heights above the bed.

Values of n, a, and c found in the generalized formula for all sizes of sand are shown in Table III. Values of both n and a increase with sand size.

Rates of Sand Flow

The area under curves similar to those of Fig. 8 will be proportional to sand loss for a vertical section equal to the width of the 0.92-inch square sampling tubes. This quantity A can be found by integrating the expression

$$x = \left(\frac{a}{y+c}\right)^{1/n}$$

between the limits of 0 and infinity for y, as follows:

$$A = \int_0^\infty x dy = \frac{nc}{1-n}\left(\frac{a}{c}\right)^{\frac{1-n}{n}}$$

If A is in units of inch-grams obtained directly from the plotting of data as shown in Fig. 8,

$$q = \frac{1.875\, A}{t}$$

in which q is in units of pounds of sand flow per foot width of bed per hour and t is the time of sampling in minutes.

Rates of sand flow calculated by the method described are given for various values of P_1 and τ_0 in Table III. The average trend of sand loss with τ_0, as determined by multiple regression, is

$$q = 175(10^3)\, d^{3/4}\, \tau_0{}^{3/2}$$

in which q is in units of pounds per foot width of bed per hour, d is in mm, and τ_0 is in pounds per square foot of bed area. The value of the index of correlation is 0.977.

Bagnold [2] found the rates of sand flow in a wind tunnel for grains from 0.1 to 1 mm in diameter to be

$$q = C\ (d/D)^{1/2}\, \frac{\rho}{g}\, (\tau_0/\rho)^{3/2}$$

in which q represents the weight of sand moving along a lane of unit width per unit time, d/D is the ratio of sand of a given diameter d to a 0.25-mm standard sand. His values of C were 1.5 for a nearly uniform sand, 1.8 for a naturally graded sand found in dunes, and 2.8 for a sand with a very wide range of grain size. Chepil [5] found that the value of C in the above formula developed by Bagnold varied from 1 to 3.1 for movement of soil particles less than 0.84 mm in diameter.

The present experimental results, expressed in the form of an equation similar to that of Bagnold [2], yield the expression

$$q = C \left(\frac{d}{D} \right)^{3/4} \frac{\rho}{g} (\tau_0/\rho)^{3/2}$$

The value of $C = 0.83$. This result indicates a considerably smaller rate of sand flow than has been obtained from previous experiments. This study has taken into consideration saltation movement only, and integration of the power function used to estimate rates of flow may miss some sand moving at or near the bed level. Again, it is believed that the writer's interpretation of τ_0 is such that greater values are obtained for a given condition. This would have the apparent effect of making the rate of sand flow relatively low.

It is of interest that the increase in the rate of sand flow with grain diameter has been found to be greater than indicated by previous investigators. In this connection it should be remarked that the turbulent boundary layer has not been developed to the maximum height of sand movement in any research to date. In the present experiment a few grains of the 0.715 mm. sand bounded to the top of the 3-foot tunnel duct. It seems obvious that the size and geometry of the tunnel duct as well as the depth of the turbulent boundary layer are factors affecting experimental results concerning rates of sand flow.

Average Height of Saltation

The height in inches above the bed y_a, above and below which equal amounts of sand were transported at the end of the bed, can also be estimated. The area under the curves of Fig. 8 between 0 and y can be expressed as

$$A_y = A \left[1 - \left(\frac{c}{y+c} \right)^{\frac{1-n}{n}} \right]$$

If y_a designates the value of y for which $A_y = A/2$, the preceding expression reduces to the form,

$$y_a = c\left(2^{\frac{n}{1-n}} - 1\right)$$

Values of y_a obtained from the above expression are given in Table III. They are plotted in relation to τ_0 in Fig. 9.

An equation for the average height of saltation and sand movement is

$$y_a = 7.7\, d^{3/2}\, \tau_0^{1/4}$$

in which y_a is the average height in inches, d is grain diameter in mm, and τ_0 is in units of pounds per square foot of bed area. A dash line,

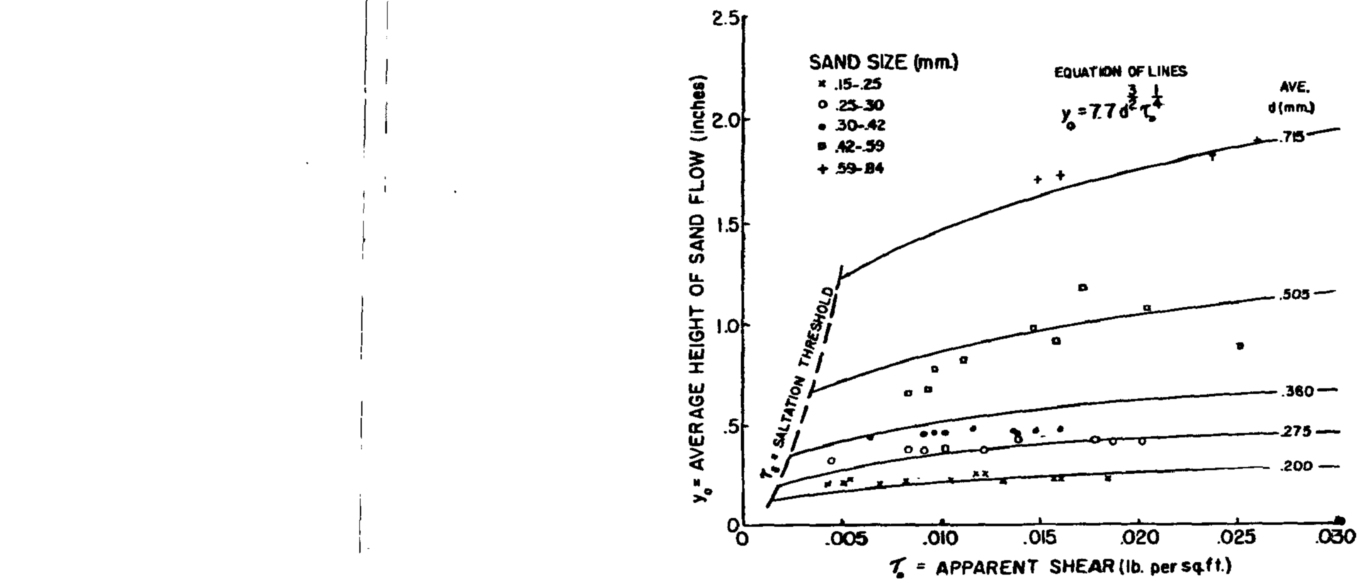

FIG. 9. AVERAGE HEIGHT OF SALTATION SAND MOVEMENT IN RELATION TO APPARENT SHEAR AND SAND SIZE.

indicating the value of the saltation threshold τ_s, above which the expression is applicable, is also shown in Fig. 9.

DISCUSSION OF RESULTS

The laboratory study of a natural phenomenon such as the one carried out here represents a highly artificial condition. The intensity of turbulence for wind tunnels can differ greatly from that of natural wind. Also, the boundary conditions common to a square duct vary greatly from those associated with atmospheric conditions. The results indicate that equilibrium flow conditions are approached over stable sand surfaces. This is not the case over the drifting surfaces as the height reached by the saltating grains exceeds the depth of the turbulent boundary layer. It would be impractical or impossible to build a tunnel wherein the field phenomenon could be approximated closely.

A technique of directly measuring shear over stable sand surfaces proved successful. The value of the universal constant $k = 0.40$ in the rough boundary equation for clear fluids was confirmed experimentally. It is of interest that the reference parameter y_1, or the height at which the logarithmic equation intersects the y axis at a projected point of zero velocity, was found to be a logarithmic function of grain diameter. This apparent fact may explain the variable results obtained by different investigators in past research.

The shape of the velocity profiles obtained over drifting surfaces varies from those secured by Bagnold [2]. The shape, however, parallels the results secured in water sedimentation research by Vanoni [11]. It appears that the value of the universal constant k in the logarithmic equation for flow over drifting surfaces is < 0.40. While a value of $k = 0.375$ has been used in the analysis of data for this experiment, it is possible that the actual value varies with the rate of sand flow and for beds formed by grains of different diameter.

A technique for determining a definable saltation threshold velocity or shear was developed. Past methods have been dependent upon visual observation and subject to personal error or judgment. The general level of the saltation threshold approximated that found in research by others. It is interesting that a greater bed shear is apparently required to move beds of sand grains in water than in air.

Equations were developed to define the distribution of drifting sand with height above the bed. Integration of the weight of sand-height function provides a method for estimating the total saltation sand flow. The procedure, however, may miss some sand flow characterized as bed movement. Since quantities of flow are substantially below those obtained by prior investigators this is possibly the case. It appears that the only way to determine the total movement accurately is to make direct weighings of the bed before and after movement occurs. This is virtually impossible for the large beds of sand used in the present experiment. Again, it would be desirable and possibly profitable to re-run the experiment with sand occupying the entire 36-inch width of the tunnel. The lateral dispersion of drifting sand from the 18-inch experimental width was not anticipated when the experiment was designed.

One of the difficulties associated with the experimental procedure was the rather involved technique of measuring a large number of variables simultaneously. Any one of the several measurements of the various phenomena are subject to rather large experimental error.

DISCUSSION

[At the close of Mr. Zingg's talk, he presented a remarkably informative slow-motion moving picture of particles in saltation. Some of the ensuing discussion refers to this film.]

Mr. Rand complimented Mr. Zingg on his contribution to the studies of the transport of sediment by flowing air. As the study of the velocity distribution is important in the paper, he felt his investigation of the velocity distribution in open channel flow over relatively rough, fixed surfaces to be relevant. He referred to the logarithmic velocity distribution as given by the formula

$$\frac{u}{\sqrt{\tau_0/\rho}} = \frac{2.3}{k} \log \frac{y}{y'}$$

If this formula is to be used, it is necessary to know the reference elevation of the bed and the values of y' and k.

Mr. Rand found that the bed elevation and the value of y' depend only on the roughness size and geometry and are invariable for a given roughness. The factor k also proved to be a function of the roughness size and geometry and of the relative roughness d/y_0. With decreasing relative roughness, k increased and approached 0.40 as limit. For instance, k for $\frac{1}{4}$-in. square-strip roughness spaced at 1-inch intervals on the bottom of the channel was 0.30 for $\frac{d}{y_0} = 0.3$ and 0.37 for $\frac{d}{y_0} = 0.003$. However, for the roughness formed by ordinary fly-screen k proved to be 0.37 to 0.40 even for the $\frac{d}{y_0}$ values up to 0.06. This difference is caused by the difference in geometry.

His results and those of Mr. Zingg are comparable, even though the roughness in Mr. Zingg's experiments was that of a moving sand surface. For the stabilized surface of fine sand the relative roughness was very small and the limiting value $k = 0.40$ could be expected. For drifting sand the relative roughness was considerably increased by the ripple formations which changed the shape and geometry of the sandy surface. The k value in this case is considerably lower than 0.40. Moreover, with increase in mean velocity, the size of ripples increased and y' increased as a function of surface geometry. This is shown in the crossing of lines on the semi-logarithmic velocity plot, indicated as a focal point by Mr. Zingg. The curvature of the semi-logarithmic velocity line near the bottom could be decreased by the proper choice of the bed elevation, which would be different for various shapes and sizes of ripples.

As the result of both investigations, it seems that k is a variable not only in sediment-bearing flow but in clear flow as well, and even if the effects of sediment are not considered, the variation of k can be at least partially explained by changes in relative roughness and roughness geometry. Of course, much more research is necessary for definition of the law of variation for k.

Mr. Leopold was particularly interested in possible applications of Mr. Zingg's studies to the geomorphology of the Mississippi River Valley. Though the deposits in that region were made primarily by flowing water, perhaps the determinations of the effects of air flow might be related. Also, the study has interesting applications in the formation of the sand dunes and loessial deposits in the central United States.

Mr. Coldwell remarked that from his experience in the dust bowl he noted that a sand storm, as distinguished from a dust storm, seemed to start at an air velocity of 18 miles per hour. He asked Mr. Zingg if his observations would bear this out.

Mr. McNown was concerned with the method of sand transport, whether by suspension or saltation, that is, by a series of projectile-like movements. He agreed with Mr. Zingg that the latter was probably the most common form of transport.

Mr. Christiansen asked about the angular deviation of the sand movement as shown in motion pictures. He also inquired concerning the symmetry of the pattern about the center of the flow.

In reply to Mr. Coldwell, Mr. Zingg said that in the field all sizes of bed material were present, ranging from fine sand to rather large gravels and that the beginning of movement was different for each. Also, the method of experimentation was quite different from normal atmospheric conditions and that comparisons were difficult. He did indicate that his observations indicated a beginning of sand movement when the wind velocity 2 feet above the field reached 8 miles per hour on the average, with some gusts. With regard to the method of movement he indicated that the particles in many cases began their movement by jumping into the flow, then on return to the bed struck other particles. They then might jump in any direction, even transverse to the flow. Those which rose high above the bed received a greater forward impetus from the moving air. In answer to Mr. Christiansen, Mr. Zingg indicated that the picture was taken along the center of the flow.

Mr. Baines pointed out by letter some recent developments in boundary-layer work with which the author may not have been acquainted. Schultz-Grunow, Klebanoff and Diehl, Wieghardt, and Baines have measured the velocity distribution on a smooth plate and Moore has measured it on rough plates. The results have been cited and correlated by Mr. Baines in a recent publication [22]. It has been concluded from these investigations that the logarithmic velocity distribution does not apply to the boundary layer for $y/\delta > 0.3$, although the parameters used in the logarithmic-velocity distribution do describe the flow. Consequently, k does not appear to have any significance.

Mr. Baines maintained that evaluation of the shear from the momentum equation prior to a comparison with the measured values would leave only those inconsistencies due to experimental inaccuracies and would eliminate the apparent divergencies noted in the paper. Until the properties of the turbulence in the boundary layer can be measured accurately and correlated to the mean flow, the analysis of the velocity distribution and sediment transportation cannot proceed beyond the present state.

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