WIND INFLUENCES ON THE TRANSPORTATION OF SAND OVER A MICHIGAN SAND DUNE

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Most of the quantitative data concerning the transport of sand by wind have been gained in the wind tunnel or in desert regions [1][1]. It therefore seemed to be of interest to obtain some factual information on sand transport in our humid regions. The project herein described was suggested by Dr. Ralph Belknap of the Department of Geology of the University of Michigan, and observations were obtained on a field trip from September 29 to

FIG. 1.—VIEW OF BLOWOUT-DUNE FROM LAKE.

October 3, 1941, under the joint sponsorship of the Department of Geology of the University of Michigan and the Institute of Meteorology of the University of Chicago.

A typical blowout (Figs. 1 and 2) near Stevensville, Michigan,

[1] References appear at the end of the article.

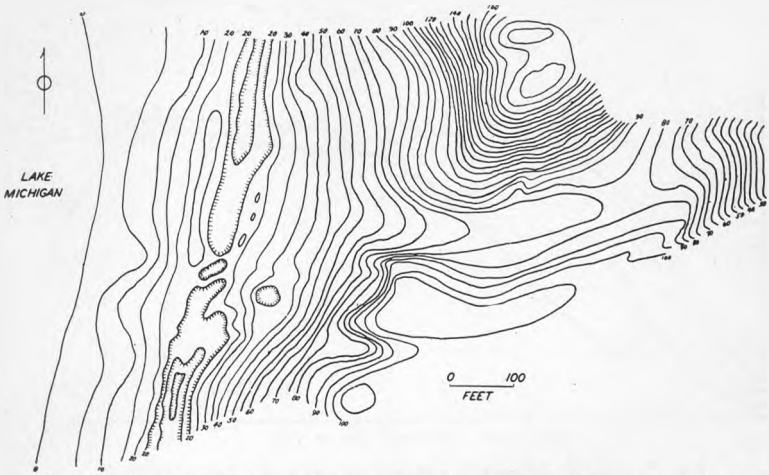

FIG. 2.—CONTOUR MAP OF BLOWOUT-DUNE. CONTOUR INTERVAL 5 FEET. ELEVATIONS ABOVE LAKE LEVEL.

on the east shore of Lake Michigan, was chosen for a set of orientation measurements. The results to be reported on here are preliminary in character, but are placed on record for an interim until times permit a more extensive study of the problem.

THE WIND STRUCTURE OVER THE DUNE

The wind structure over the dune was obtained by horizontal and vertical profiles of wind velocities at a number of points. All measurements were made with Biram Anemometers. Fig. 3 shows the mean relative velocities over the dune. Near the beach a very good logarithmic profile of the wind velocities was obtained. In the front portion of the blowout, where it was cut deeply into the old dune ridge, the vertical velocity profile was much disturbed. The channeling effect of the front slope and the two ridges to either side of the blowout created much higher velocities nearer the ground than elsewhere. The velocities were practically uniform from 50 centimeters to 10 meters.

From all available data the average small-scale roughness coefficient for the blowout was calculated to be 0.13 centimeters. This is a remarkably low value, which indicates that the wind action on the dune had streamlined its surface to a considerable extent.

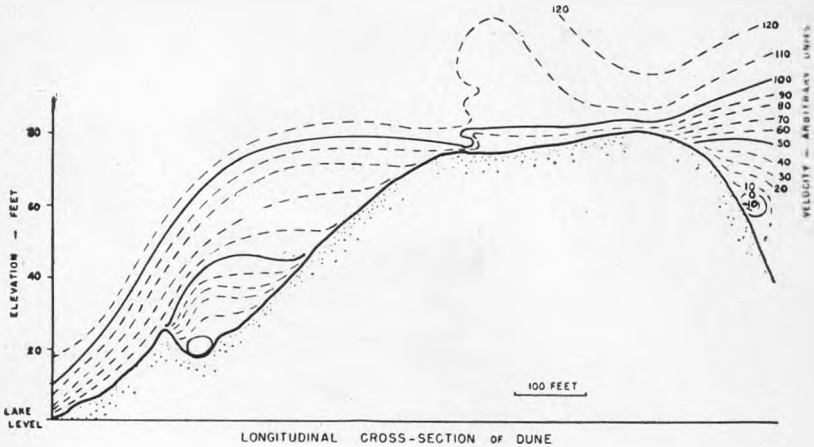

FIG. 3.—MEAN RELATIVE VELOCITIES OVER BLOWOUT-DUNE IN ARBITRARY UNITS.

GEOMETRICAL PROPERTIES OF THE SAND

In an attempt to evaluate the relation of the observed wind distribution to the transported sand, a brief study was made of the geometrical properties of the sand. Nine 500-gram samples (Fig. 4) were collected along a longitudinal profile of the blowout from the

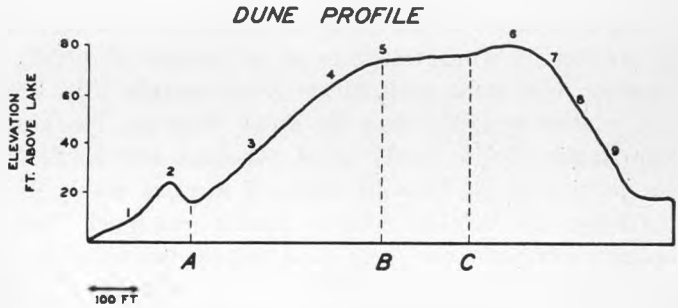

FIG. 4.—DUNE PROFILE SHOWING SAMPLING LOCALITIES.

fore dune to the base of the back slope. A thin surface layer from approximately one square foot was collected. A 100-gram split from each large sample was sieved by hand in the field to whole Wentworth grades. Samples of the same size were later sieved in the laboratory for seven minutes in a Ro-Tap to one-quarter Went-

worth grades. The sieve data for the laboratory-sieved samples are given in Table 1. The moments of the size distribution were calculated in ϕ units [2]—i.e. $\phi = -\log_2$ (grain diameter in millimeters)—and the values for both the laboratory and field-sieved samples are given in Table 2. It is interesting to note the close agreement between the crude field sieving and the accurate laboratory sieving.

A graph showing mean size-distance, and the standard deviation of the size-distance, is given in Fig. 5. The mean diameter of sand and standard deviation of sand-size distribution, both in phi units,

TABLE 1
SIEVE DATA TO ONE-QUARTER WENTWORTH GRADES
WEIGHT PERCENT

d Grain diameter (mm)	ϕ $-\log_2 d$	Sample No.									
		1	2	3	4	5	6	7	8	9	10
.991	0.00	0.19	0	0.10	0.13	0	0.04	0	0	0	T
.840	0.25	0.10	0	0.15	0.08	0	0.04	0	0	T	T
.701	0.50	0.13	T	0.26	0.14	0	0.1	0	0	T	T
.589	0.75	0.45	0.09	0.68	0.56	0.11	0.75	T	0.12	0.12	T
.495	1.00	1.1	0.64	1.52	1.42	0.10	2.39	0.05	0.41	0.34	0.14
.417	1.25	2.6	2.72	3.59	4.15	0.47	8.14	0.35	1.32	1.88	0.72
.351	1.50	9.7	12.30	9.51	13.85	3.61	25.70	3.64	10.11	15.86	5.01
.295	1.75	22.5	25.30	16.65	23.06	12.95	29.15	15.82	31.06	40.55	15.66
.246	2.00	36.5	36.20	30.26	26.00	41.47	22.02	36.50	34.22	28.18	34.74
.208	2.25	15.9	13.95	17.19	14.55	23.71	6.25	20.02	10.92	7.05	19.40
.175	2.50	9.3	7.22	14.02	12.28	14.14	4.42	17.55	9.22	4.96	18.99
.147	2.75	1.1	0.91	5.48	2.95	3.04	0.65	3.51	1.61	0.51	3.38
.124	3.00	0.26	0.48	0.37	0.51	0.66	0.44	2.03	0.83	0.80	2.32
.104	3.25	0.12	0.06	0.37	0.38	0.18	0.02	0.36	0.04	0.01	0.19
.088	3.50	0.02	0.01	T	T	T	T	0.10	T	T	0.05
.074	3.75	T	T	T	T	T	T	T	0	T	T
.061	4.00	T	T	T	T	T	T	T	0	0	T

A. FIELD SIEVED TO WHOLE WENTWORTH GRADES

Sample	Mean Size mm	M_ϕ	σ_ϕ
1	0.29	1.80	0.40
2	0.29	1.79	0.35
3	0.29	1.80	0.50
4	0.31	1.74	0.40
5	0.30	1.78	0.31
6	0.35	1.55	0.35
7	0.26	1.92	0.33
8	0.31	1.70	0.30
9	0.33	1.63	0.22

TABLE 2

B. LABORATORY SIEVED TO ONE-QUARTER WENTWORTH GRADES

Sample	Mean Size mm	M_ϕ	σ_ϕ	K_ϕ
1	0.27	1.88	0.31	—0.68
2	0.28	1.83	0.29	0.10
3	0.26	1.92	0.39	—0.64
4	0.27	1.86	0.41	0.20
5	0.27	1.88	0.37	0.08
6	0.32	1.63	0.32	0.02
7	0.25	2.02	0.31	0.33
8	0.28	1.86	0.29	0.14
9	0.30	1.75	0.26	0.22
10	0.25	2.02	0.34	0.32

are plotted against distance. The solid circles are the result of field sieving; the dashed circles, laboratory sieving.

In general, between the beach and point A (Fig. 4) sand is

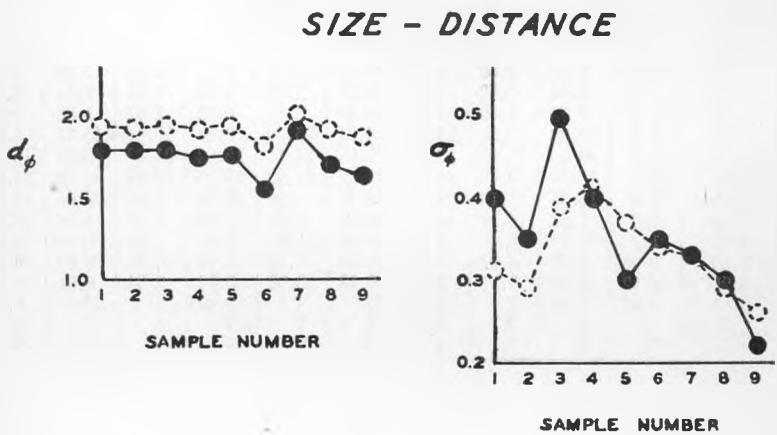

FIG. 5.—MEAN DIAMETER AND STANDARD DEVIATION OF SIZE DISTRIBUTION.

being deposited; between A and B erosion is cutting into the old dune at all places; between B and C erosion is decreasing and deposition occurs. Between the beach and A, therefore, the wind acts selectively on the original sand, and gradients in the geometrical properties of the sand should be observed. From A to the break in the dune slope at B, although the sand is selectively transported over this area, various amounts of sand from various horizons

of the old dune are being added to the transported sand (Fig. 6). Any gradients due to selective transportation would necessarily be hidden by the complexity of the admixture. From B to the base of the back slope, however, erosion is progressively decreasing and the effects of selective transportation become evident. The relations should be further simplified by the uniform surface-wind configuration (Fig. 3).

FIG. 6.—EROSIONAL SURFACE OF OLD DUNE.

From the crest of the dune, at sample 6, to the base, the deposition of the sand is controlled by two factors: Stokes-law settling, and gravity slumping of single storm deposits.

No attempt was made to evaluate the sampling error, so it is not known whether the variations observed are true variations or are the result of random sampling. With respect to the standard deviation ("sorting") of the sand-size distribution, however, the probability of observing such an order by random sampling is one in one hundred. In other words the poorest sorting of the transported sand is observed in the region of maximum erosion and the best sorting in the region of maximum deposition.

The projection sphericity [3] of twenty-five particles in the ½- to ¼-millimeter grade size was determined for each sample. The mean and the standard deviation of the distribution for each

sample are plotted against distance in Fig. 7. The variations observed are small and show no progressive change that cannot be due to random sampling.

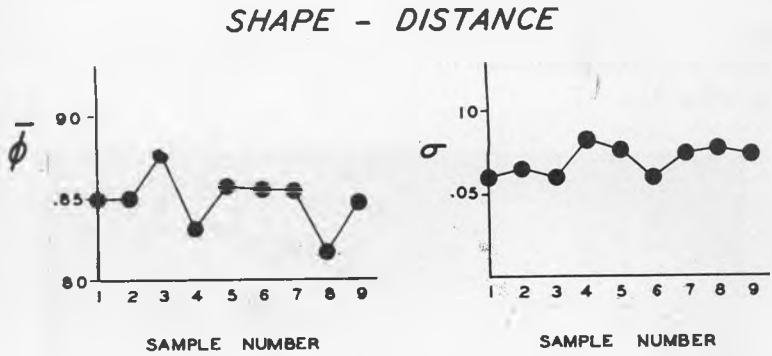

FIG. 7.—SPHERICITY AND STANDARD DEVIATION OF SPHERICITY DISTRIBUTION.

DYNAMICS OF SAND TRANSPORT

On September 30, 1941, a high wind (Beaufort force 6-7) after the passage of a cold front started considerable movement of sand. Particles struck the faces of the observers, indicating transport to at least 6 feet high. In the lowest layers the transport was so dense that it could readily be photographed (Fig. 8). The rain

FIG. 8.—VIEW OF BLOWING SAND.

stopped at 1340 (1:40 P.M.) on that day and sand blowing was observed almost immediately afterwards. This observation indicates that even with considerable moisture content sand transport is possible. Table 3 shows the moisture content of the surface sand.

TABLE 3

MOISTURE CONTENT OF THE SAND

Sept. 30 to Oct. 2

Elapsed Time (after rain)	Percent Moisture
20 min.	4.4
50 min.	4.4
2 hr.	4.4
3 hr.	3.4
6 hr.	4.3
19 hr.	2.5
23 hr.	2.6
47 hr.	1.5

At 1450 on September 30 a sampling bag was fixed at the top of the blowout in the form of a wind sock with the lowest edge touching the ground. The bag offered an opening 31 square centimeters in area. The average wind velocity for the sampling period of five minutes was 10 meters per second at a height of 65 centimeters. During that time 405.5 grams of material was collected, or 81.1 grams per minute, corresponding to 2.6 grams per square centimeter per minute. The sand was very moist and sticky, as proven by difficulty in sieving. The size distribution is given under sample number 10 in Table 1. Table 2 gives the mean size, standard deviation, and skewness.

This sample shows in comparison with the values in Table 2 the highest percentage of the finer grades, as would be expected for a wind-blown sample. The mean diameter was 0.28 millimeter. Our observed sand transport may now be compared with Bagnold's data. Our data would correspond to a transport of 78 kilograms of sand per hour per meter width; for the same wind velocity (10.8 meters per second at 1 meter), Bagnold's diagram ([1] p. 63) would yield an expected value of 150 kilograms per hour per meter width. Our observations thus show only 50 percent of Bagnold's theoretical transport; as suggested to the writers by W. C. Krumbein, this could be due to the moisture content of the sand. The total quantity of sand transported through the blowout is impressive. On the basis of observations during ten hours of sand

blowing in this storm, approximately 90 tons of material was blown through this rather narrow blowout.

On several occasions it was possible to determine the threshold velocity at which sand was starting to move. The mean value of these measurements, obtained at 5 centimeters above the surface, yielded a value of 3.5 meters per second.

One of the most important questions regarding sand transport is the vertical distribution of sand grains in a sand cloud. Measurements were made by exposing vaseline-coated microscope slides at various heights above the ground and counting the particles caught. Fig. 9 shows the observed distribution of sand particles deposited

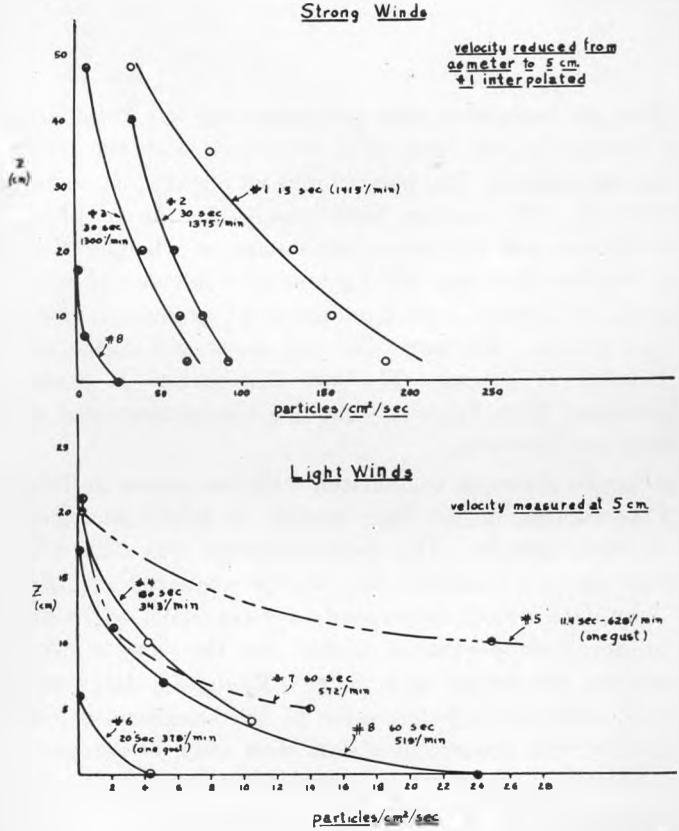

FIG. 9.—VERTICAL DISTRIBUTION OF PARTICLES PER SQUARE CENTIMETER AT DIFFERENT WIND VELOCITIES.

per square centimeter per second at various heights for a number of different wind velocities. In some cases the exposure lasted only for a single gust of ten to twenty seconds. If the transport of sand were the result of turbulent suspension under equilibrium conditions, the distribution of particles could readily be obtained from the following two equations, of which the first expresses balance between Stokes-law settling and turbulent transfer upward, and the second gives an expression for the wind stress in terms of eddy viscosity and wind shear:[1]

$$\rho N c = - \eta_1 \frac{\partial N}{\partial z} \tag{1}$$

$$\tau = \eta_2 \frac{\partial u}{\partial z} \tag{2}$$

It is generally assumed that η_1 and η_2 are identical. Hence division gives

$$\ln \frac{N_1}{N_2} = \frac{c}{\tau/\rho} (u_2 - u_1)$$

Testing this hypothesis with the data on hand, it is found that observation shows relatively too few particles close to the surface and too many particles at higher levels. This discrepancy is undoubtedly due primarily to the saltation phenomenon which, according to Bagnold, is solely responsible for sand transport in the desert. Further, it should be mentioned that the samples were collected over time intervals from eleven seconds to three minutes in duration, which are too short to assume equilibrium conditions of either the wind or the sand transport.

In instantaneous vertical wind distributions—i.e., for a gust—the logarithmic distribution breaks down, and during such a gust, of course, it cannot be assumed that the sand would assume equilibrium with the environment. This points to the necessity of measuring the strength and frequency of the gusts simultaneously with measurement of sand movement. This has not yet been done, but preliminary data on gustiness were obtained.

[1] Notation: N = density of suspension, ρ = density of air, c = velocity of free fall of particles, η_1 = eddy diffusivity, η_2 = eddy conductivity, z = height, u = wind velocity at height z, τ = shear stress.

If the velocity fluctuations, u' and w' in the x and z directions, are random, then the temporal mean of the product of these fluctuations is zero—i.e., $\overline{u' w'} = 0$. This mean is zero only when u is constant with elevation. If u varies with elevation, then $\overline{u' w'}$ is different from zero and a negative correlation exists between u' and w'. This correlation is

$$r = \frac{\overline{u' w'}}{(\overline{u'^2}\ \overline{w'^2})^{1/2}}$$

The shearing stress, τ, has been shown by O. Reynolds to be equal to $-\rho\ \overline{u' w'}$. Introducing this relation into the above ratio and assuming equipartition of turbulent kinetic energy, the ratio becomes

$$r = -\frac{\tau/\rho}{\overline{u'^2}}$$

One-minute velocity measurements over the dune were analyzed following the above procedure. The values of the correlation at various heights are:

Height above ground in meters	0.5	1	2	4	5	6	7.7
$-r$	0.51	0.31	0.28	0.23	0.27	0.23	0.22

The standard deviation of the horizontal velocity fluctuations is therefore practically independent of height within the vertical range studied and is proportional to the mean wind at a standard reference height. The values obtained are in fair agreement with results of small-scale laboratory experiments [4].

REFERENCES

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[4] von Kármán, Th., "Turbulence and Skin Friction," *Jour. Aero. Sci.,* Vol. 1, 1934.