Threshold Velocities and Initial Particle Motion as Influenced by Air Turbulence

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SOIL particles move in response to the dynamic forces generated by fluid flow. A wind strong enough to produce soil-particle movement is always turbulent (Chepil and Woodruff, 1963). Sutherland (1966) has stated that grains cannot be lifted from the bed in water without the presence of turbulent fluctuations adjacent to and directed toward the bed.

Although it has been recognized that velocity and pressure fluctuations influence threshold or critical values of drag or of velocity for initiating sand or soil movement, quantitative information is limited. Kalinske (1943) has suggested that the local longitudinal-turbulence intensity, $\sigma_u/\bar{u}_z$, is about 33 percent near the bed. Assuming a normal distribution of velocity fluctuations, instantaneous velocities would be twice the mean, and momentary values of drag would be four times the mean. Earlier, White (1940) had made a similar observation.

Chepil and Woodruff (1963), summarizing earlier work, accounted for the effects of turbulence by including a turbulence factor, T, in an equation for the critical drag, τ_c. T, reported to have an average value of 2.5, was obtained from the equation:

$$T = \frac{3\sigma_p + \bar{P}}{\bar{P}} \qquad [1]$$

where σ_p is the root-mean square (RMS) of pressure fluctuations and $\bar{P}$ is the mean pressure. In the actual data, T varied between about 2.1 and 3.0.

Few writers have attempted to describe exactly the initial motion of the first particles moved by fluid. Most workers agree that the grain motion in air, once initiated, is maintained by a process called saltation; i.e., particles that leave the bed but are too large to be suspended by the flow, return to the bed to initiate movement of other grains. Most writers have been satisfied by Bagnold's (1943) statement: "A critical windspeed was reached when the surface grains, previously at rest, began to be rolled along the surface by the direct pressure of the wind. A foot or so downwind of the point at which the rolling began, the grains could be seen to have gathered sufficient speed to start bouncing off the ground." Similar statements by others can be found (Chepil, 1945a; Chepil and Woodruff, 1963; Malina, 1941).

Bisal and Nielsen (1962) seemingly are the only writers who have challenged that description of movement of the first grains. They placed a mixture of erosive and nonerosive particles in a small, shallow pan mounted on the viewing stage of a binocular microscope to observe the particles as the airstream over the pan was increased. Concluding that the majority of erosive particles vibrated with increasing intensity as windspeed increased and then left the surface instantaneously (as if ejected), they attributed the motion to impulse forces caused by pressure fluctuations. Because they gave nothing about turbulent properties of the flow, further experimentation is needed to relate the vibrations, if observed, to other flow parameters.

A logical hypothesis would seem to be that particle oscillation occurs when dynamic-lift forces approach critical levels resulting from varying pressures and velocities caused by turbulent eddies in a steep velocity gradient near the bed. A corollary would be that the particle-oscillation frequency is related to the spectral band containing the maximum turbulent energy. Consequently, measurements of the spectral distribution of the energy of the longitudinal fluctuations are needed to determine the frequency band containing the peak energy.

Here we report on effects of local turbulence intensity on threshold conditions for particle motion and on observations of the initial motion of erodible sand or soil particles in a wind-tunnel boundary layer.

EXPERIMENTAL PROCEDURE

In the wind-tunnel facility, described previously (Lyles et al., 1969), free-stream, longitudinal-turbulence intensity was about 1.7 percent.

Various levels of turbulence intensity were generated by spherical particles with narrow size distributions, which covered the downwind length of the tunnel floor (Table 1). The local longitudinal component for the surfaces studied is shown in Fig. 1.

TABLE 1. SUMMARY OF DATA ON SURFACES COMPOSED OF SPHERICAL PARTICLES

Surface identification	Average diameter, cm	Standard deviation, cm	Geometric standard deviation	Areal density, number per sq cm
S_1	0.606	0.022	1.04	2.87
S_2	1.641	0.062	1.04	0.41
S_3	2.453	0.072	1.03	0.18

Free-stream velocity was measured with a pitot-static tube connected to a sensitive, differential-pressure transducer whose output was summed with an integrating digital voltmeter. Local mean velocity at any height in the boundary layer could then be determined from profiles measured earlier (Lyles, 1970).

The spectrum of turbulence (i.e., the frequency distributions of the eddy motion in the longitudinal direction) was measured by connecting a wave analyzer to the output of a constant-temperature, hot-wire anemometer and linearizer.

Shallow trays (approximately 2 x 9 in.) were constructed in such a way that the spheres glued in them had the same elevation as the surrounding spheres. The trays, filled with erodible-sized sand or soil grains (struck off with a straightedge passed across the top of the spheres), were oriented with the long dimension normal to the mean flow about 36 ft downwind in the tunnel. The erosive grains (a river sand and a silt loam soil) were separated in three size fractions by a Ro-tap sieving machine (Table 2).

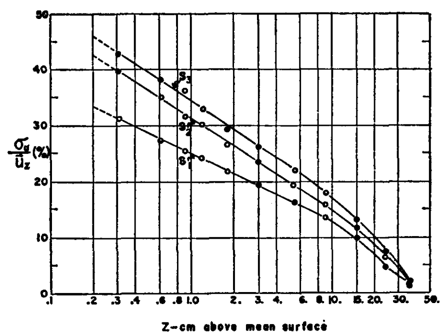

Fig. 1 Local longitudinal-turbulence intensity over rough surfaces

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TABLE 2. SIZE RANGE AND DENSITY OF ERODIBLE GRAINS

Erodible material	Particle-size range, mm	Particle density, g per cu cm
Sand	0.177-0.297	2.60
Sand	0.42 -0.59	2.59
Sand	0.59 -0.84	2.59
Soil	0.42 -0.59	1.60

Threshold velocities of the particles were determined two ways. First, for S_2 and S_3, a rough quantitative measure was obtained by observing the trays through a telescope and noting on a velocity-printout chart the points where these criteria were met: (a) motion of first grain, (b) a few grains moving intermittently, (c) gusts of grains moving intermittently, and (d) general bed movement. Second, the filled trays were weighed, exposed to increasing mean windspeeds for 1 to 3 min, and reweighed. Weight loss versus mean windspeed was plotted, and the curve relating them was projected to near zero loss. The mean windspeed at that point was considered the threshold velocity. The friction velocity, u_*, was computed from the adiabatic mean windspeed profile equation:

$$\bar{u}_z = \frac{u_*}{k} \ln\left(\frac{Z-D}{Z_0}\right) \qquad [2]$$

where $\bar{u}_z$ is the mean velocity at height Z above some reference elevation; u_* is the friction velocity, defined as $(\tau_0/\rho)^{1/2}$ where τ_0 is the shear stress at the boundary and ρ is fluid density; k is von Karman's constant (0.4); D is an effective roughness height; and Z_0 is a roughness parameter.

The small trays were also used to study the motion of the largest grains before translation occurred. The initial grain motion was observed through a 12-power telescope located outside the wind tunnel. Motion pictures of the grains, viewed from above the trays, were also made as mean windspeed was gradually increased. Particle-vibration frequency was determined by counting vibrations, observed through the telescope, and by counting 6.1-mm tapioca spheres covering the floor of the wind tunnel at free-stream velocities of 16.3 m per sec.

Experimental Data and Observations

Only the peak frequency of the longitudinal energy spectra is reported (Fig. 2). The correlation coefficient between peak frequency and height in the boundary layer was not significant at the 5 percent level, and surface roughness seemed not to influence peak frequency. Therefore, all peak-frequency data could be averaged to give 2.3 ± 0.7 Hz.

Initial Particle Motion

As the mean windspeed approached the threshold value, some particles began to vibrate, or rock back and forth, as indicated by Bisal and Nielsen (1962). The vibrations were seldom steady. After flurries of 3 to 5 vibrations, the particles ceased vibrating momentarily before vibrating again or before leaving the tray. When mean windspeed was increased considerably above the threshold, the particles moved from the tray so rapidly that particle vibration could not be observed. These observations were confirmed by motion pictures.

Good estimates of the particle-vibration frequency were difficult to obtain because of the unsteady motion. Average vibration frequency of the 0.59- to 0.84-mm sand grains was 1.8 ± 0.3 Hz. By one observer the tapioca spheres averaged a vibration frequency of 1.8 ± 0.3 Hz, and by another, 2.1 ± 0.2 Hz.

Threshold Conditions

Threshold-friction velocities averaged for the two roughest surfaces (S_2, S_3), determined by visual observation, are presented in Fig. 3.

The curves for S_3, relating sand or soil loss from the small trays and free-stream velocity, are shown in Fig. 4. The mean velocity extrapolated to 0.001 g per min per sq in. sand or soil loss was considered the threshold mean windspeed. The logarithmic scale for sand loss was chosen because the theoretical threshold velocity at which the loss curve extrapolates to zero would be difficult to determine on a linear scale, on which the curve would approach the velocity coordinate tangentially. Because no zero loss point can be established on a log scale, an arbitrary value of loss was chosen to identify the threshold velocity. The threshold windspeeds at 1.22 cm above the mean surfaces (chosen because it is well into the region where equation [2] is valid) are shown in Table 3.

TABLE 3. THRESHOLD WINDSPEED, $\bar{u}_t$, FOR INDICATED PARTICLE-SIZE RANGE OVER THREE SURFACES

Erodible material	Particle-size range, mm	$\bar{u}_t$ at 1.22 cm, cm per sec S_1	S_2	S_3
Sand	0.177-0.297	415	363	335
Sand	0.42 -0.59	617	498	448
Sand	0.59 -0.84	699	568	539
Soil	0.42 -0.59	499	419	385

Table 4 contains the corresponding information on the friction velocities, computed from the logarithmic law using the mean windspeed profile parameters for the appropriate surface. Threshold mean velocities decreased as local turbulence-intensity (surface roughness) increased (Table 3). However, the lower mean velocities were offset by higher turbulent-velocity fluctuations; and threshold-friction velocities for a given particle-size range were approximately equal, regardless of turbulence intensity (Table 4).

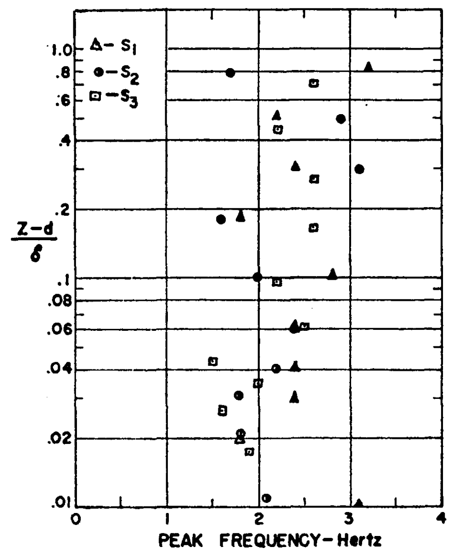

Fig. 2 Peak frequency of the longitudinal-energy spectrum; d is the zero plane displacement and δ is the boundary-layer depth

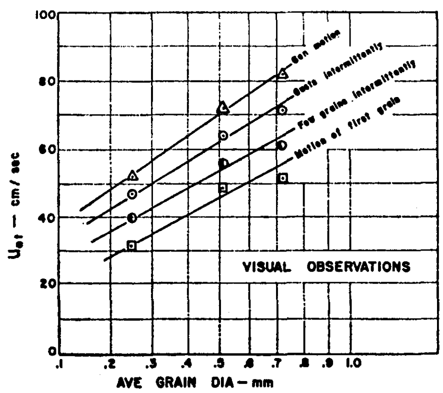

Fig. 3 Threshold-friction velocities based on visual observation of grain motion (abscissa in square-root scale)

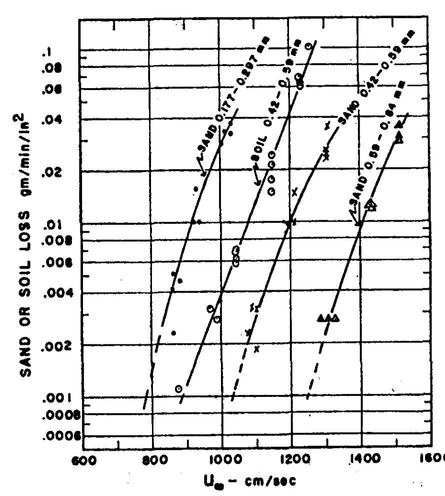

Fig. 4 Sand or soil loss versus free-stream velocity for S_3

TABLE 4. THRESHOLD-FRICTION VELOCITIES, u_{*t}, FOR INDICATED PARTICLE-SIZE RANGE OVER THREE SURFACES

Erodible material	Particle-size range, mm	u_{*t}, cm per sec S_1	S_2	S_3	Ave.
Sand	0.177-0.297	41.9	44.3	46.0	44.1
Sand	0.42 -0.59	62.3	60.7	61.2	61.4
Sand	0.59 -0.84	70.7	69.4	72.9	71.0
Soil	0.42 -0.59	50.4	51.2	52.1	51.2

Interpretations and Discussion

Average particle-vibration frequency (1.8 Hz) probably was lower than average peak frequency of the longitudinal fluid spectrum (2.3 Hz) because of the large difference between the mass density of erodible particles and fluid. Assuming the peak frequency of the longitudinal spectrum to be normally distributed, the average particle-vibration frequency fell well in the range of 0.2 to 4.4 Hz, supporting the hypothesis that particle-vibration frequency is related to the frequency band containing the maximum energy of the turbulent motion.

The threshold-friction velocities obtained here were considerably larger than those obtained by other workers (Fig. 5). Data labeled "Chepil-computed" shown in Fig. 5 were derived from this equation for critical drag (Chepil, 1959).

$$\tau_c = \frac{0.66\, g\, d_p\, \rho'\, \eta \tan\phi'}{T(1 + 0.85 \tan\phi')} \quad [3]$$

In that equation, g is the gravitational constant; d_p is the minimum grain diameter; ρ' is immersed density of the grain; η is the ratio of drag on the whole bed to drag on an exposed particle; ϕ' is an angle related to the grain angle of repose and the point where average drag acts on the grain; and T is a turbulence factor defined in equation [1].

Differences in values obtained by us and those obtained by other workers possibly could be explained by: (a) different definitions of "Threshold" conditions, (b) errors in various terms of equation [3], (c) errors in determining u_* from mean velocity measurements, (d) wrong assumptions about stress acting on boundary, and (e) different experimental techniques.

Bagnold's (1943) data apparently were based on visual observations of the movement of the first grain or few grains, and Zingg's (1953) on actual shear measurements just large enough to sustain grain motion. Zingg's procedures to determine threshold conditions resulted in a large experimental error.

A range of values was obtained for the various terms in equation [3]. Selected choices for the size of the terms, in the range covered, produced rather large changes in the computed friction velocities. The term, η, apparently a function of exposed grain size, increased as grain size decreased instead of remaining constant, as assumed by Chepil (1959) (Fig. 6). From the regression equation of Fig. 6, η varied from 0.81 to 0.97 for the erodible grain sizes studied. It seems logical that as the grain size approached zero, η would approach 1.

A turbulence factor, T, could be computed using an approach similar to Chepil's (1959), but using velocity fluctuations in lieu of pressure fluctuations:

$$T = \left[\frac{\bar{u}_z + 3\sigma_u}{\bar{u}_z}\right]^2 \quad [4]$$

$$\text{or } T = \left[1 + 3\left(\frac{\sigma_u}{\bar{u}_z}\right)\right]^2 \quad [5]$$

The square was used because pressure or drag is proportional to mean velocity squared. Because $\sigma_u/\bar{u}_z$ is a function of surface roughness, T could not be a constant in equation [5] but would increase with increasing surface roughness. Using $\sigma_u/\bar{u}_z$ values at 0.3 cm above the surfaces (the lowest elevation measured), T values for S_1, S_2, and S_3 were 3.76, 4.83, and 5.24, respectively. Assuming those values for T and η from the regression equation, threshold-friction velocities were computed from equation [3]. The average values (labeled "computed" in Fig. 5) agreed closely with average measured values. Based on the above assumptions in equation [3], threshold-friction velocity should decrease for a given particle size as turbulence intensity increases (roughness increases). This could not be verified from the experimental data of Table 4.

We assumed that the thin strip of erodible grains would experience the same stress and turbulence as the spheres covering the wind-tunnel floor. But, Schlichting (1960), citing Jacobs, stated that when going from a rough to a smooth surface, the smooth surface at the boundary immediately takes on the shear stress that would have been produced if the entire upwind surface were smooth. To test that conclusion, we mounted the small tray of large spheres (S_3) on cantilever beams whose deflection was sensed by a proximity probe. Actual drag measurements were made with and without the sand grains at three windspeeds. The shear stress calculated from the logarithmic law and the measured shear stress were almost identical (Table 5). There was no indication that the smoother sand-grain surface experienced a lower shear stress than did the 2.45 cm spheres.

TABLE 5. DRAG MEASUREMENTS ON A SMALL TRAY OF 2.45-CM SPHERES, WITH AND WITHOUT ERODIBLE SAND GRAINS

u_*, cm per sec	τ, g per sq cm Computed	Measured with sand	Measured without sand
42.86	0.0021	0.0020	0.0022
62.92	0.0046	0.0046	0.0046
78.35	0.0071	0.0073	0.0072

Bagnold (1943) and Chepil (1945b) did not mention corrections applied to

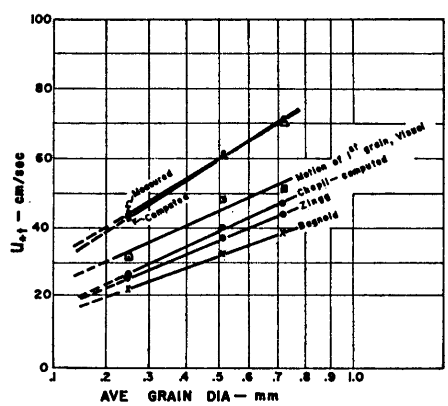

Fig. 5 Threshold friction velocities of several workers compared (abscissa in square-root scale)

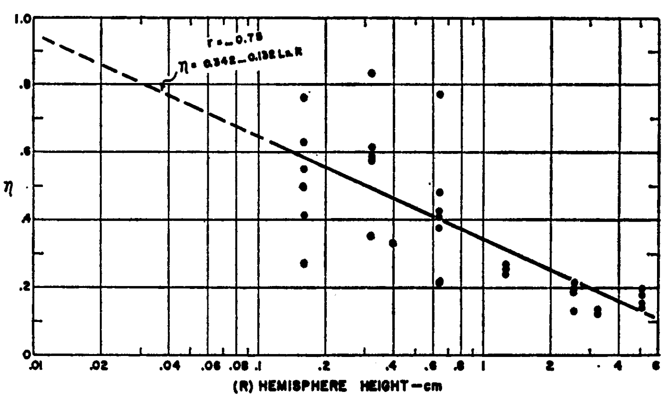

Fig. 6 Exposed particle drag, related to hemisphere height. Data from Chepil (1959, 1961)

their mean-velocity data collected with a combined pitot-static tube. Consequently, u_* computed from their mean-velocity profiles might be inaccurate. They also used slightly different forms of the logarithmic-law equation for the mean velocity profile.

Bagnold (1943) used an experimental coefficient, A, similar to Shield's (1936) (but using the friction velocity u_* in lieu of the shear stress at the boundary τ_0) to describe the threshold friction velocity. The expression is:

$$A = \frac{u_{*t}}{(\alpha\, gd)^{1/2}} \qquad [6]$$

in which α is the apparent density ratio ρ'/ρ. The value of A (in air), as found by Bagnold (1943), was 0.10 for nearly uniform sand grains of diameters $\geqq 0.2$ mm. Later Chepil (1945b) obtained values of 0.09 to 0.11 and Zingg (1953) obtained an A value of 0.12, both in air. For unexplained reasons, Shield's (1936) values of A were greater in water than in air and varied from about 0.18 to 0.22 in the turbulent range. In a later paper, Bagnold (1951) discussed why A is different in air and water.

The values of A obtained in this study are given in Table 6. They ranged from 0.17 to 0.20, based on average grain diameter; and from 0.19 to 0.23, based on minimum grain diameter. The values for air agreed closely with those for water, suggesting that a difference in the coefficient between the two fluids might not exist.

Summary

Threshold conditions for particle motion were determined over three surfaces, with known levels of local turbulence intensity, in a wind-tunnel boundary layer. The study included spectral analyses of the longitudinal turbulent motion and observations of the initial motion of erodible sand or soil particles.

Neither surface roughness nor height of measurement in the boundary layer was observed to influence peak frequency of the longitudinal-energy spectra. Average value of the peak frequency was 2.3 ± 0.7 Hz.

As mean windspeed approached the threshold value, some particles began to vibrate, or rock back and forth; that agreed with findings of some Canadian workers. Average vibration frequency was 1.8 ± 0.3 Hz, which supported the hypothesis that the particle-vibration frequency is related to the frequency band containing the maximum energy of the turbulent motion.

Threshold mean windspeed for a given particle-size range decreased as longitudinal-turbulence intensity increased. However, experimentally determined values of the threshold-friction velocities, u_{*t}, were approximately the same regardless of turbulence intensity. Threshold-friction velocities obtained in this study were considerably larger than those obtained by other workers. Several possible reasons for the differences were discussed.

Values of the dimensionless coefficient, A, in the equation $A = \frac{u_{*t}}{(\alpha\, gd)^{1/2}}$, determined in this study for air agreed closely with those determined by Shields (1936) for water; they contrasted with lower values obtained by Bagnold (1943), Chepil (1945b), and Zingg (1953) for air and suggested that the coefficient was the same for both fluids.

TABLE 6. VALUES OF COEFFICIENT A OVER THREE SURFACES. $A = \frac{u_{*t}}{(\alpha\, gd)^{1/2}}$

Erodible material	Particle-size range, mm	A			
		S_1	S_2	S_3	Ave.
Sand	0.177-0.297	0.18	0.19	0.20	0.19
Sand	0.42 -0.59	0.18	0.18	0.18	0.18
Sand	0.59 -0.84	0.18	0.17	0.18	0.18
Soil	0.42 -0.59	0.19	0.19	0.20	0.19
Ave.	-	0.18	0.18	0.19	0.185

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