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BOUNDARY-LAYER FLOW STRUCTURE: EFFECTS ON DETACHMENT OF NONCOHESIVE PARTICLES 1/

by

Leon Lyles and N. P. Woodruff 2/

SYNOPSIS

Discussed in this report are (a) the mean-velocity profile and the parameters of a selected equation, (b) factors influencing turbulence intensity in the boundary layer, (c) the motion of the first particles to be moved, and (d) the influence of turbulence intensity on threshold conditions for erodible particles.

Data presented show that: (a) the logarithmic law should be fitted only to mean-velocity data from the lower 20 percent of the boundary layer; (b) mean velocity cannot be used to characterize critical conditions for particle movement unless surfaces are similar; (c) turbulence intensity is influenced by size, shape, and arrangement of elements causing roughness in neutral flows; (d) the ratio σ_u/u_* in the "constant-stress" layer is essentially constant and independent of surface roughness; and (e) dimensionless turbulence parameters and the coefficient A in the equation $u_{*t} = A(\alpha g d)^{1/2}$ are similar in magnitude for air and water. Symbols are defined in the text.

Information presented confirms Canadian research indicating vibratory motion by particles before translation and shows that average particle-frequency vibration is related to the frequency band containing the maximum turbulent energy. Experimentally determined threshold-friction velocities for a given particle-size range were approximately equal regardless of turbulence intensity.

INTRODUCTION

Worldwide, erosion of land surfaces by water is variously estimated to contribute from 3.8 to 58 x 10^9 metric tons of sediment to the oceans each year (1). In the United States an estimated 4 billion tons of sediment are washed from the land into various tributaries each year (2). Although sediment eroded by wind is only about 1 percent of the amount of sediment carried by streams (1), wind contributes significantly to erosion in the Great Plains and Far West, and where there are coastal sands, organic soils, and interior sandy soils.

Wadleigh (2) has estimated that each year 30 million tons of natural dusts enter the U. S. atmosphere. But that amount represents only about 5 to 40 percent of the total amount of particles moved by wind (3).

Soil particles move in response to the dynamic forces generated by fluid flow. In air, a wind strong enough to move soil particles is always turbulent (3). In water, according to Sutherland (4), particles cannot be lifted from the bed without turbulent fluctuations adjacent to and directed toward the bed.

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2/ Agricultural Engineer and Research Investigations Leader, Soil Erosion, USDA, Manhattan, Kansas.

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 (5) has suggested that the local longitudinal-turbulence intensity, $\sigma_u/\bar{u}_z$, is about 33 percent near the bed. σ_u is the root-mean square (RMS) of velocity fluctuations in the mean flow direction measured at the same height Z as the mean velocity $\bar{u}_z$. 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. White had made a similar observation (6).

Chepil and Woodruff (3), 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 ranged from about 2.1 to 3.0.

MEAN VELOCITY PROFILE AND PARAMETERS

Turbulence is related to the mean properties of the flow upon which it is superimposed. Consequently, if we are to make application of results, reliable data on mean properties are essential.

For aerodynamically rough flows, some form of the logarithmic law is used almost universally to describe the mean-velocity profile near the boundary. We prefer this form for adiabatic flows:

$$\bar{u}_z/u_* = \frac{1}{k}\ln\left(\frac{Z - D}{Z_o}\right) \qquad (2)$$

where $\bar{u}_z$ is the mean velocity at height Z, u_* is the friction velocity defined as $(\tau_o/\rho)^{1/2}$ where τ_o is the shear stress at the boundary and ρ is fluid density, k is von Karman's constant (0.4), Z is the height of measurement from some reference plane, D is an "effective" height of roughness, and Z_o is a roughness parameter.

Almost without exception, those who have reported on rough-boundary flows have noted the uncertainty in determining the origin of the height coordinate normal to the boundary. The height,d, at which the mean-velocity profile extrapolates to zero is equal to D + Z_o.

The "constant-stress" layer, or the interior portion of the boundary layer where the logarithmic law fits the mean velocity measurements, is restricted to about 0.2δ, or 0.2$\bar{d}$ where δ is the boundary-layer depth and $\bar{d}$ is the total depth of flow in an open channel. Many workers do not make sufficient measurements in the restricted zone to obtain accurate values for the parameters D, Z_o, and u_*. Also, there is a temptation to fit the logarithmic law to data that include points outside the "constant-stress" layer. Lyles (7), after considering the effect on the profile parameters of using data beyond the limits of the logarithmic law and of using mean-velocity data taken with a pitot-static tube not corrected for the effects of turbulence, concluded: Z_o and D were very sensitive to velocity data outside the "constant-stress" layer, and the friction velocity (u_*) was (depending on surface roughness) 17 to 40 percent larger for profiles involving data over the lower 50 percent of the boundary layer compared with those involving data only from the lower 15 percent. Data corrected for turbulence were 2 to 8 percent larger than uncorrected data.

The mean-velocity profile is controlled by the nature of the surface (Fig. 1). Mean velocities are lower over rough surfaces than over smooth surfaces at similar heights near the boundary, even if free-stream velocities are identical. Consequently, mean velocities are not good indicators of the stress at the boundary unless the flows in question are occurring over similar surfaces. Furthermore, mean velocity may be misleading if comparisons are made for flows over surfaces with different degrees of roughness.

Sutherland (4) and Rathbun and Guy (8), who found critical (threshold) mean velocities for particle movement to be less for dune or ripple-covered beds than for flat or plane beds, suggested that turbulence intensity influences the transport of sediment.

We agree with those statements on turbulence intensity. They clearly show the fallacy of using mean velocity to indicate critical conditions when the nature of the surfaces is different. The friction velocity can be larger for a rough than for a smooth surface, even though the mean velocity in the boundary layer at similar heights is lower for the rough surface.

TURBULENCE CHARACTERISTICS

The general influence of surface roughness on turbulence-intensity space components is well known. The specific relationships for the local longitudinal component on a smooth surface (S_1) and on surfaces of spheres with diameters of 0.61 cm. (S_2), 1.64 cm. (S_3), and 2.45 cm. (S_4) are shown in Fig. 2 (9). In the boundary layer, local intensity increases toward the surface and obviously increases with increasing roughness over the range of roughness tested. Turbulence intensity was related not only to the size of roughness elements but also to their shape and arrangement (Fig. 3).

In the "constant-stress" layer, the ratio of the RMS of velocity fluctuation (σ_u) to the friction velocity (u_*) was essentially constant and independent of surface roughness (Fig. 4). The average value of the longitudinal constant, $C = \sigma_u/u_*$, was 2.33, which agreed closely with monin's (10) data for neutral atmospheric flow and with Laufer's (11) data for pipe flow.

Turbulence data are much more limited for liquid flows than for air; however, Fig. 5 shows a similar magnitude for local longitudinal-turbulence intensity in air and water. The rough surfaces represented in Fig. 5 were not composed of similar elements. At heights of Z/δ less than 0.2, only one or two measurements were made in the water channel.

From turbulence measurements in water made by Richardson and McQuivey (12), values of σ_u/u_* ranged from 2.0 to 2.7 near the boundary, in general agreement with those for air. From measurements in a viscous oil made by Clyde and Einstein (13), σ_u/u_* ranged from 2.0 to 2.8 at values of $Z/\bar{d}$ between 0.01 and 0.08; the overall average, about 2.3, was almost identical to that we obtained in air. Generally one can conclude that the dimensionless-turbulence parameters for air and liquids are similar in magnitude.

PARTICLE MOTION AND THRESHOLD CONDITIONS

Few writers have attempted to describe exactly the initial motion of the first particles moved by fluid. In constrast to statements by Bagnold (15) and Chepil (16), Bisal and Nielsen (17) reported that erodible particles oscillate or vibrate before translation. Lyles (7) confirmed Bisal and Nielsen's observations for wind-tunnel boundary-layer flows; he noted that particles vibrated unsteadily (flurries of 3 to 5 vibrations with momentary cessations) before they again vibrated or left the bed. The average vibration frequency was 1.8 ± 0.3 Hz. He hypothesized that

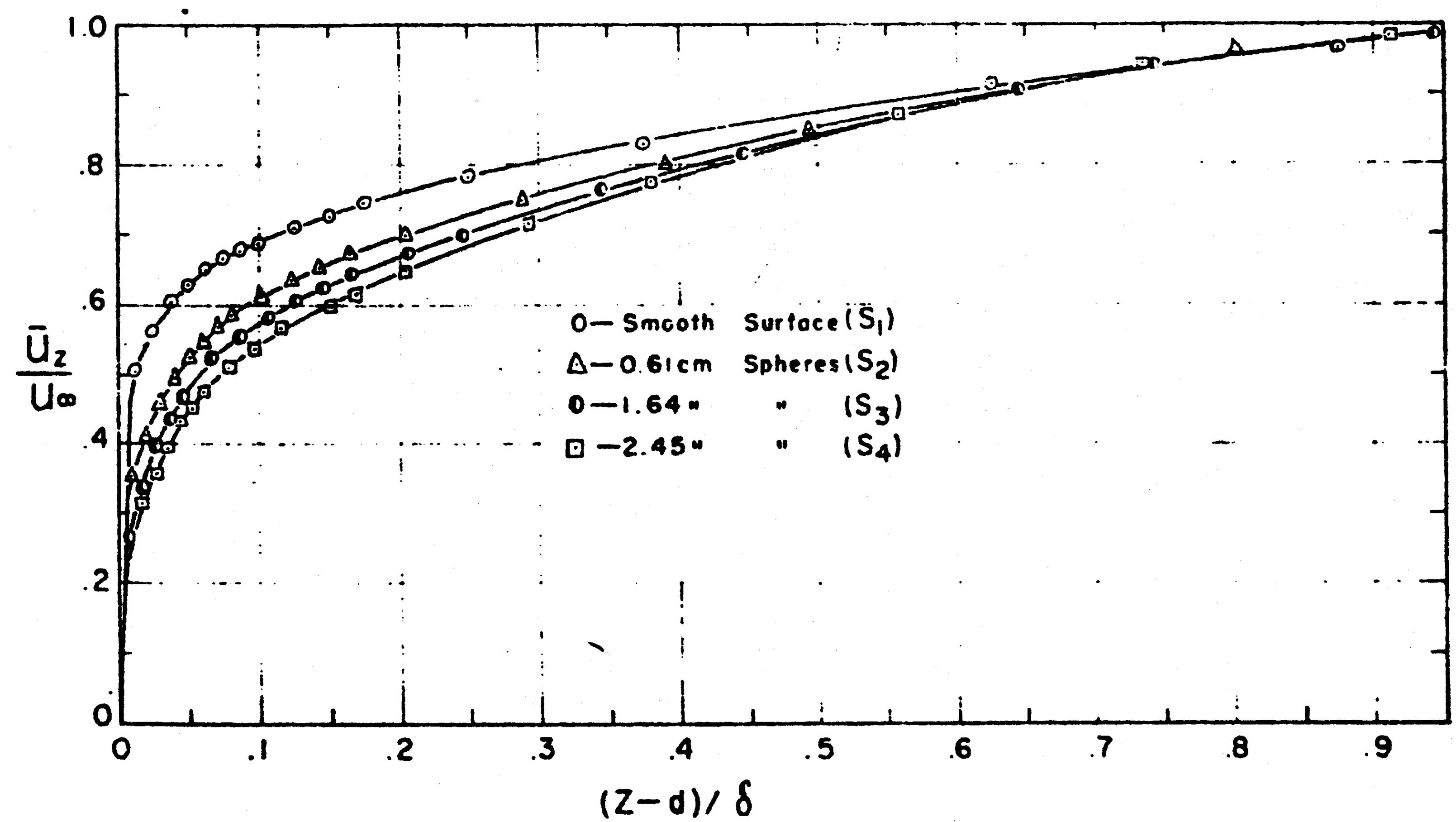

Figure 1.--Turbulent mean-velocity profiles in the boundary-layer over smooth and rough surfaces (7); wind tunnel data. u_∞ is free-stream velocity.

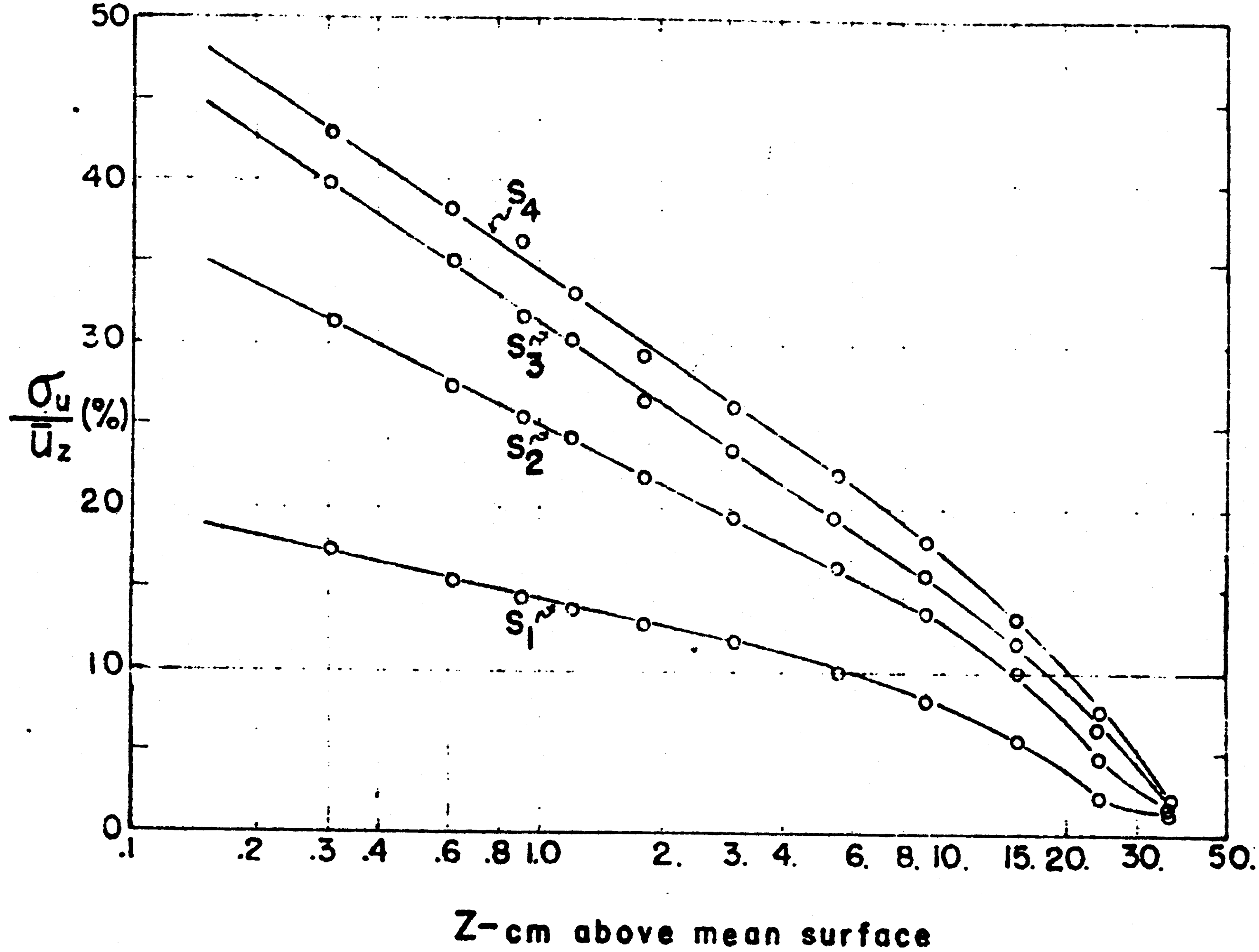

Figure 2.--Local longitudinal turbulence intensity over smooth and rough surfaces; wind tunnel data. Symbols are identified in figure 1.

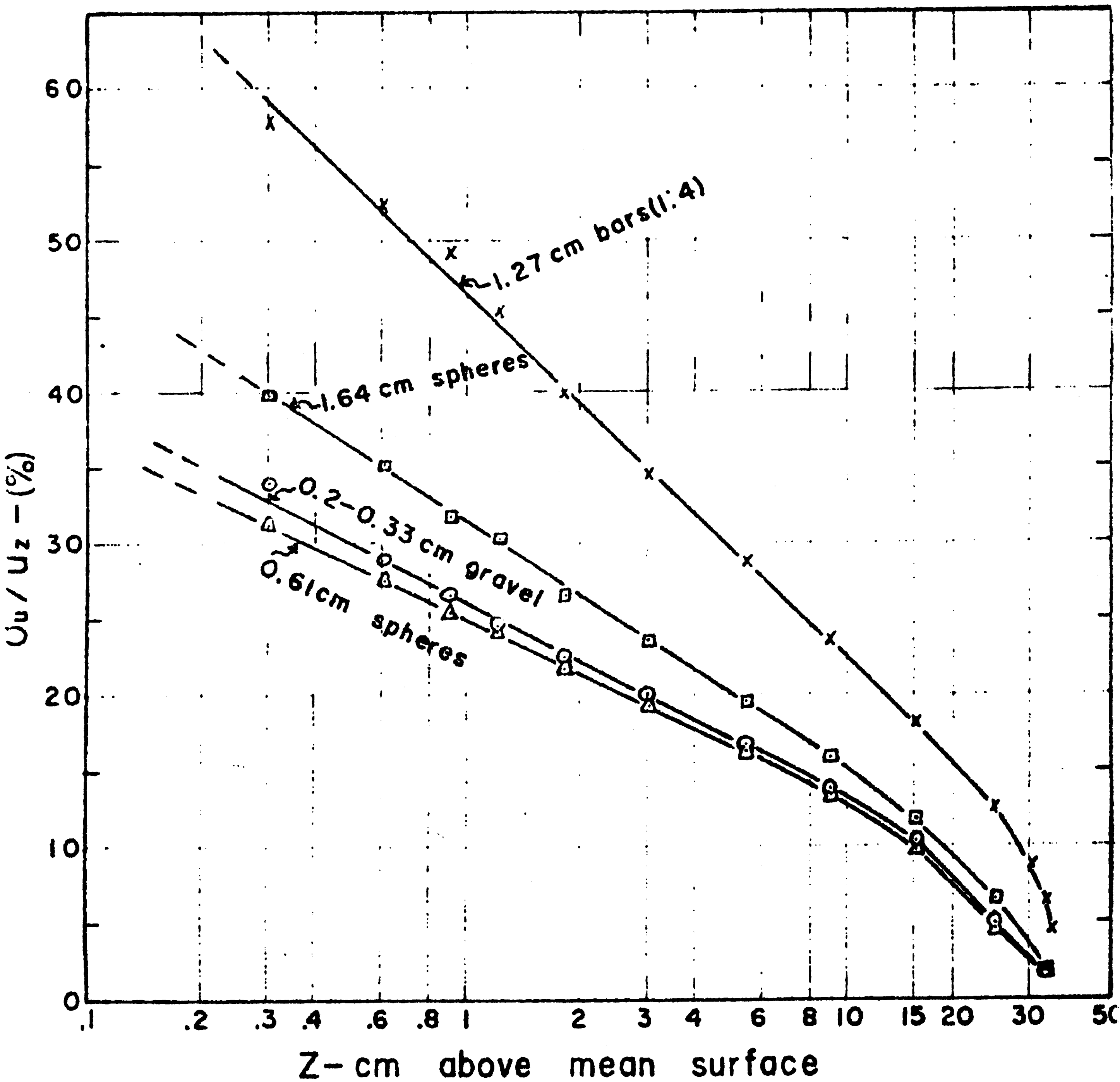

Figure 3.--Effect of shape and arrangement of roughness elements on longitudinal turbulence intensity; wind tunnel data. The (1:4) ratio refers to a 1-to-4 height spacing for the square bars.

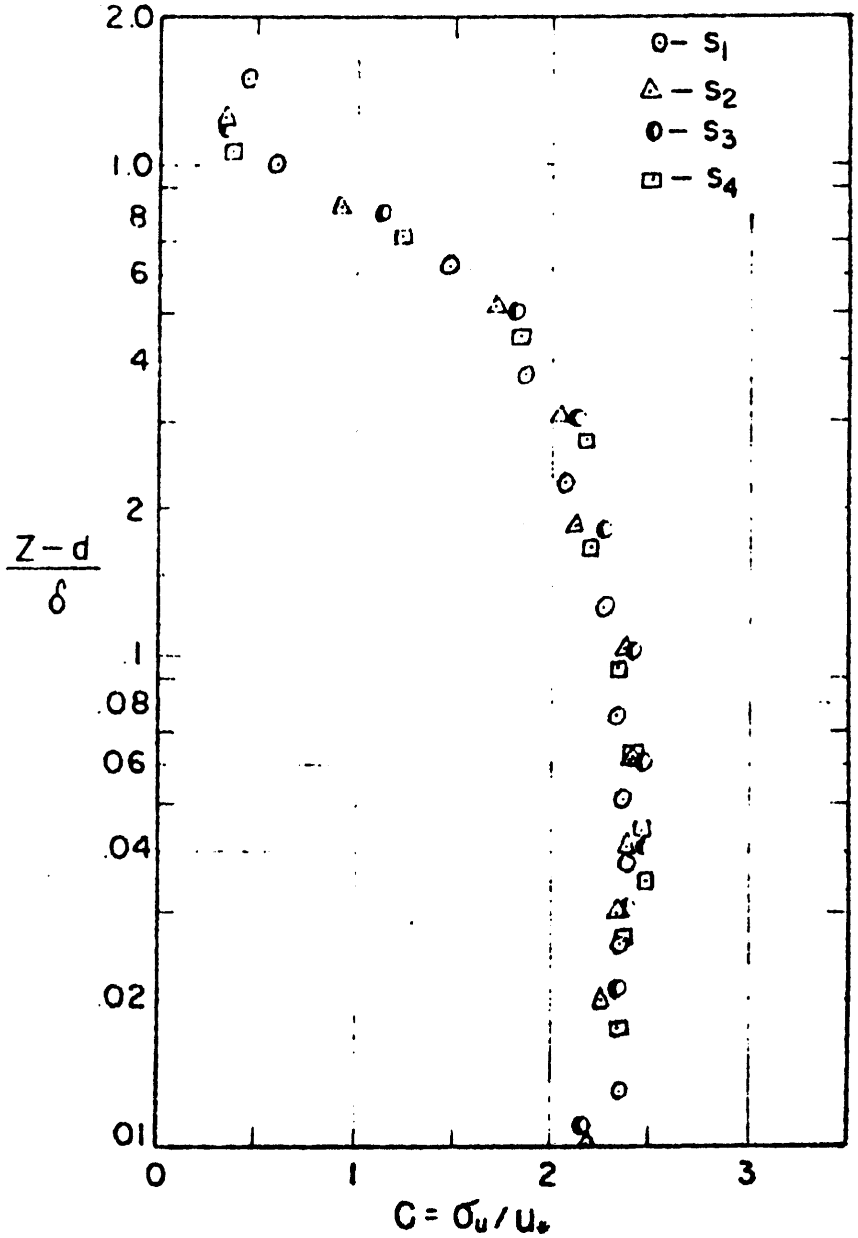

Figure 4.--C values for four surfaces in relation to boundary-layer depth (7); wind tunnel data. Symbols are identified in figure 1.

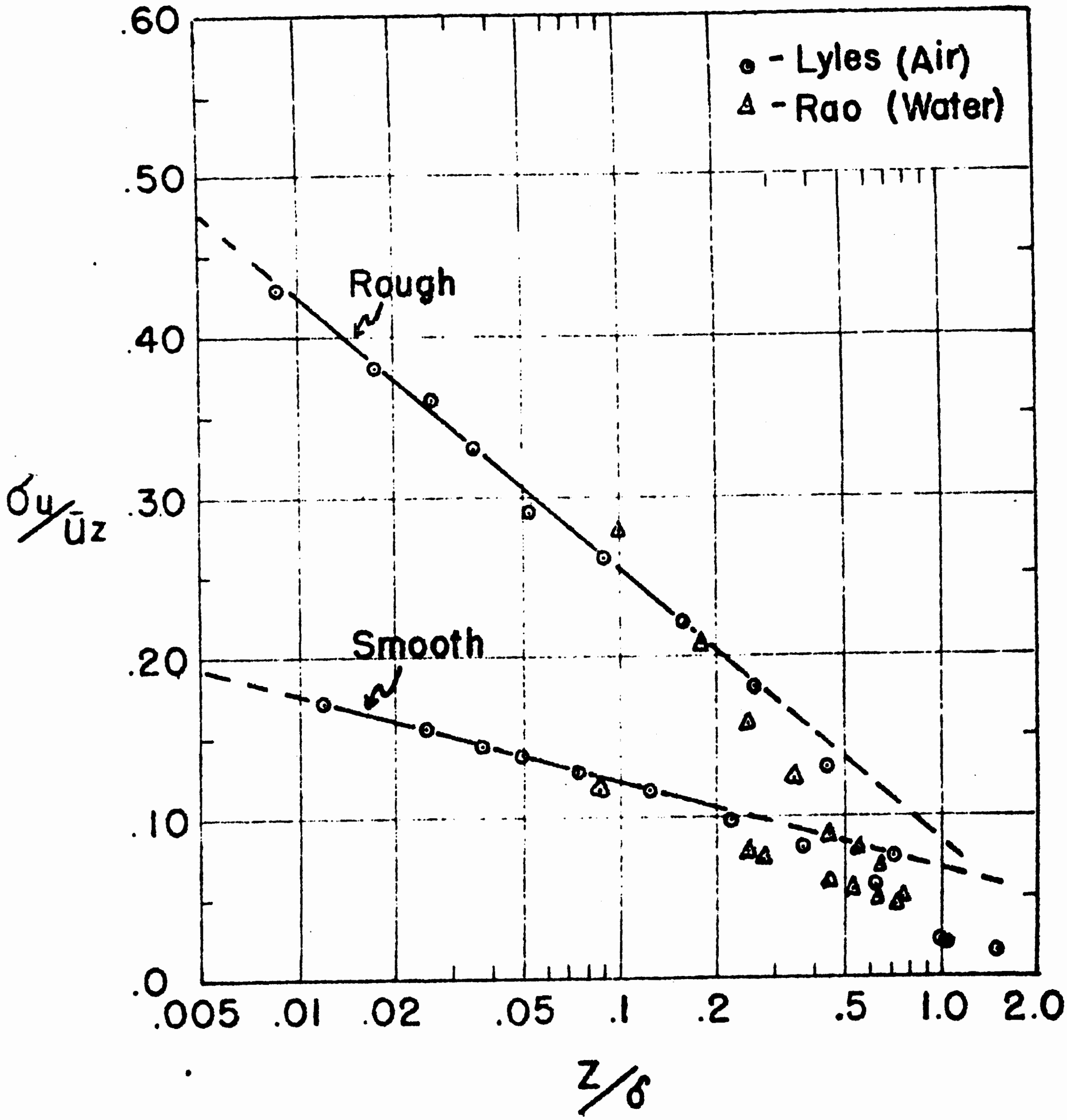

Figure 5.--Local longitudinal turbulence intensity in air and water over smooth and rough surfaces (7, 14).

the 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. Additionally he hypothesized that the particle-oscillation frequency is in the spectral band containing the maximum turbulent energy but somewhat lower than the fluid peak frequency because of particle mass. The latter hypothesis was supported by an average-peak frequency of 2.3 $\pm$ 0.7 Hz. for the longitudinal spectrum, which was independent of both elevation in the boundary layer and surface roughness (Fig. 6).

Threshold mean velocities for three sizes of sand grains and one soil grain decreased as local turbulence intensity (surface roughness) increased (Table 1). 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 2).

Table 1. Threshold Windspeed, $\bar{u}_t$, for Indicated Particle-Size Range over Three Surfaces. S_2, S_3, and S_4 are 0.61, 1.64, and 2.45 Cm. Spheres, Respectively. Data from Lyles and Krauss (18).

Erodible material	Particle-size range	$\bar{u}_t$ at 1.22 cm. above mean surface		
		S_2	S_3	S_4
	mm.	cm./sec.		
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

As mentioned earlier, Chepil (19) developed this equation for critical drag:

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

where g is the gravitational constant, d_p is 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 angle of repose of the grains and the point where average drag acts on the grain, and T is a turbulence factor defined in Eq. (1).

Table 2. Threshold-Friction Velocities, u_{*t}, for Indicated Particle-Size Range over Three Surfaces, S_2, S_3, and S_4 are 0.61, 1.64, and 2.45 Cm. Spheres, Respectively. Data from Lyles and Krauss (18).

Erodible material	Particle-size range	u_{*t}			
		S_2	S_3	S_4	Ave.
	mm.	cm./sec.			
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

Lyles and Krauss (18) have shown that the term, η, is a function of exposed grain size rather than a constant, as assumed by Chepil. They reported this regression equation for η:

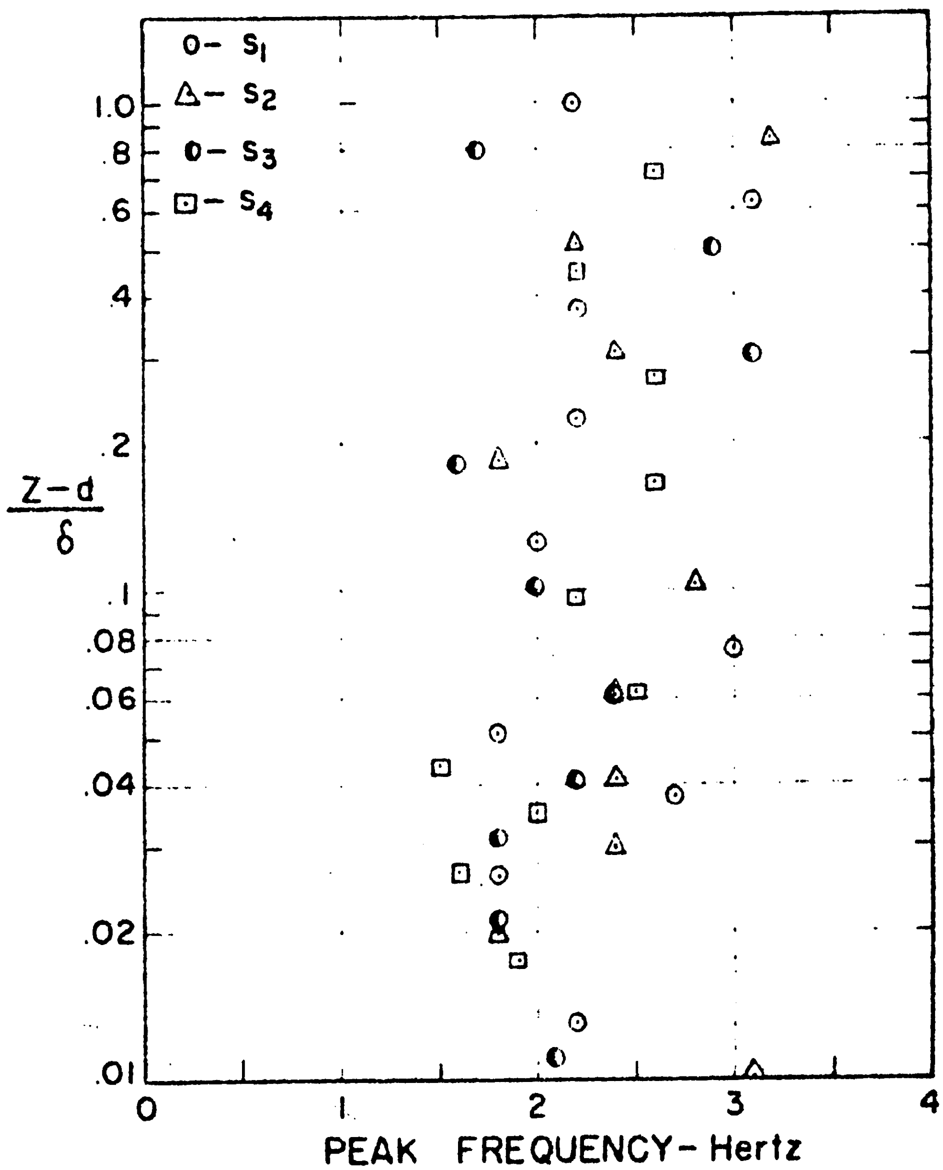

Figure 6.--Peak frequency of the longitudinal-energy spectrum (7); wind tunnel data. Symbols are identified in figure 1.

$$\eta = 0.342 - 0.132 \ln r \tag{4}$$

where r is the radius in centimeters of the exposed grains (values of r should be restricted so that η does not exceed 1).

A turbulence factor, T, was computed using velocity fluctuations in lieu of pressure fluctuations (18):

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

Because $\sigma_u/\bar{u}_z$ is a function of surface roughness, T could not be a constant in Eq. (5) but would increase with increasing surface roughness. Using $\sigma_u/\bar{u}_z$ values at 0.3 cm. above the surface, T values for S_2, S_3, and S_4 were 3.76, 4.83, and 5.24, respectively. Assuming those values for T and η from Eq. (4), threshold-friction velocities were computed from Eq. (3) (Table 3). The average computed values agreed closely with average measured values in Table 2. Based on the above assumptions in Eq. (3), threshold-friction velocity should decrease for a given particle size as turbulence intensity (roughness) increases. That could not be verified from the experimental data of Table 2.

Bagnold (15) used an experimental coefficient, A, similar to Shields's (20) (but using the friction velocity u_* in lieu of the shear stress at the boundary, τ_o) to describe the threshold friction velocity. The expression is:

$$u_{*t} = A(\alpha g d)^{1/2} \tag{6}$$

in which α is the apparent density ratio ρ'/ρ and d is particle diameter. The value of A (in air), as found by Bagnold, was 0.10 for nearly uniform sand grains of diameters $\geq$ 0.2 mm. Later Chepil (16) obtained values of 0.09 to 0.11, and Zingg (21) obtained an A value of 0.12, both in air. For unexplained reasons, Shields's (20) values of A (0.18 to 0.22 in the turbulent range) obtained in water were greater than those obtained in air. In a later paper, Bagnold (22) suggested that A values for air and water differ because (a) shear stress is found in different ways, (b) many measurements are made by "eye" (involving personal judgment), (c) surface packing may be different, and (d) measurements in air must be made in totally enclosed wind tunnels.

Table 3. Threshold-Friction Velocities Computed from Eq. (3).

Erodible material	Particle-size range	u_{*t} S_2	S_3	S_4	Ave.
	mm.	cm./sec.			
Sand	0.177 - 0.297	47.2	41.6	39.9	42.9
Sand	0.42 - 0.59	68.1	60.1	57.7	62.0
Sand	0.59 - 0.84	78.5	69.3	66.5	71.4
Soil	0.42 - 0.59	53.5	47.2	45.3	48.7

We obtained A values in air ranging from 0.17 to 0.20, based on average grain diameter (Table 4); and from 0.19 to 0.23, based on minimum grain diameter (18). These values for air agreed closely with those for water, suggesting that the coefficient is the same for the two fluids.

Table 4. Values of Coefficient A over Three Surfaces. S_2, S_3, and S_4 are 0.61, 1.64, and 2.45 Cm. Spheres, Respectively. Data from Lyles and Krauss (18).

Erodible material	Particle-size range	u_{*t} S_2	S_3	S_4	Ave.
	mm.	cm./sec.			
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	0.18	0.20	0.19

FUTURE STUDY

Future research should involve the influence of turbulence on threshold conditions for erodible particles, using a more independent method of generating different levels of turbulence.

A comprehensive study of particle vibration is needed to (a) investigate the effects of particle size and density on the vibration frequency, (b) determine conditions for the onset of vibration, (c) estimate the proportion of total particles that vibrate, and (d) devise accurate methods to measure vibration frequency.

Probably the most immediate need is to evaluate the effects of sediment on the mean and turbulent properties of boundary-layer flows.

NOTATIONS

The following symbols are used in this paper:

A	Constant
C	Constant
D	Effective height of roughness
d	Zero velocity plane displacement
d_p	Particle diameter
$\bar{d}$	Total depth of water
g	Gravitational constant
k	von Karman's constant
$\bar{P}$	Mean pressure
r	Radius of particle
T	Turbulence factor
$\bar{u}_Z$	Mean velocity at height Z
u_∞	Free-stream mean velocity
$\bar{u}_t$	Threshold mean velocity
u_*	Friction velocity
u_{*t}	Threshold friction velocity
Z	Vertical coordinate
Z_o	Roughness parameter
α	Apparent density ratio
δ	Boundary layer depth
η	Ratio of drag on bed to drag on exposed particle
ρ	Fluid density
ρ'	Immersed particle density
σ_p	Root-mean-square of pressure fluctuations
σ_u	Root-mean-square of longitudinal velocity fluctuations
τ_c	Critical drag
τ_o	Shear stress at boundary
ϕ	Angle

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