How Aerodynamic Roughness Elements Control Sand Movement

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SOIL erosion and other exchange processes involving heat and mass transfer are determined by wind distribution in and above roughness elements at the surface. Various structures of mean velocity and turbulence will occur, depending on the characteristics of the roughness elements. Even if a surface has only one type of roughness element, the flow will depend not only on form and height, but also on the number of roughness elements per unit area and the manner in which they are distributed. A knowledge of the effect of roughness on the flow field may suggest the best spacing of crops for erosion control.

Chepil and Woodruff (1963) defined a critical surface-barrier ratio (CSBR) as the distance between nonerodible surface barriers, L_x, divided by the height of the barrier, H, that will prevent wind from moving the erodible particles. Earlier, Chepil (1950) called the reciprocal of this ratio a critical surface-roughness constant.

On cultivated soil, L_x/H has a value of 4 to 20, depending on the friction velocity of the wind and on the threshold friction velocity of the erodible soil particles (Chepil 1958). However, the ratio reportedly remains constant for any proportion and size of nonerodible fractions present in the soil.

Here we report on the effects of various arrays of cylinders and spheres in controlling sand movement in a wind-tunnel boundary layer.

EXPERIMENTAL PROCEDURE

The experimental variables are summarized in Table 1. The nonerodible cylinders were wood doweling and the spheres were glass. Each cylinder (3.81 cm long) was placed with its axis normal to the wind-tunnel floor.

The erodible particles from a local river sand were separated into the two size fractions by sieving. Particle density was 2.63 g per cu cm.

The wind-tunnel facility (1.52 m wide, 1.93 m high, and 16.46 m long) was a recirculating push-type with free-stream, longitudinal-turbulence intensity of 1.7 percent. Airflow was generated by a 10-blade, variable-pitch axivane fan. We used a test strip (45.72 cm wide) centrally located along the tunnel floor. The remaining floor area was covered with closely packed, 1.59-cm-diameter glass spheres.

The study involved 107 tests. A typical run involved placing the nonerodible material of appropriate shape and size at a given spacing in the test strip (0.457 m wide by 16.46 m long). Over the last 11.89 m of the 16.46-m-long strip, the empty spaces among the nonerodible material were filled with erodible particles to the exact height of the nonerodible material. A mean windspeed profile of the boundary layer at windspeeds below the threshold of the erodible particles was obtained from a pitot-static tube traverse, located 14.46 m downstream over an open-ended tray (40.64 by 45.72 cm) filled with the same type of material contained in the upwind and downwind areas. Mean windspeed was increased above the threshold and maintained until sand movement was less than 0.1 g per min, as measured in Bagnold catchers whose slot width was 0.95 cm (Bagnold 1943). Two additional sand-loss measurements were taken at successively lower windspeeds to obtain losses less than 0.01 g per min. Sand-loss rate vs. free-stream windspeed was plotted, and the windspeed associated with a sand loss rate of 0.01 g per min was defined as the stable-surface windspeed (Fig. 1). Another velocity profile was obtained, and the average height of the exposed nonerodible material was determined by weighing the calibrated tray before and after wind exposure.

Mean windspeed was raised (over the previous stable surface) and additional erosion continued until sand movement was again less than 0.1 g per min. The sand-loss, velocity-profile, and height measurements were repeated for this new surface. This procedure was repeated for two or three higher windspeeds.

Using a constant-temperature hot-wire anemometer and linearizer traverse,

TABLE 1
IDENTIFICATION OF EXPERIMENTAL VARIABLES

Variable	Symbol	Identification
Shape and size of nonerodible material		
Cylinders — wood doweling	C_1	0.655 ± 0.007 cm diameter
Cylinders — wood doweling	C_2	1.589 ± 0.018 cm diameter
Spheres — glass	D_1	2.434 ± 0.067 cm diameter
Spacing of nonerodible material		
Spacing 1, diagonal array	S_1	5.08 cm center-to-center
Spacing 2, diagonal array	S_2	10.16 cm center-to-center
Size of erodible material — river sand		
Size 1	d_1	0.15 to 0.42 mm diameter
Size 2	d_2	0.42 to 0.59 mm diameter
Windspeed		
Windspeed 1 to 4	$\overline{u}_1$ to $\overline{u}_4$	Above threshold for particle size in question, cm per sec

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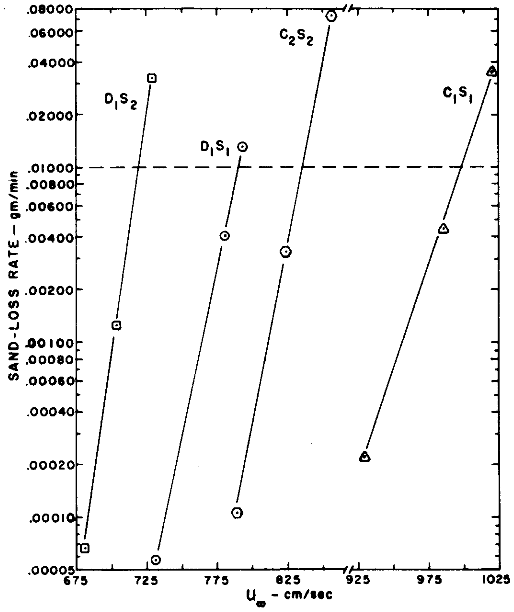

FIG. 1 Typical sand-loss rates versus free-stream velocity for several sizes and spacings of roughness elements. The dashed line indicates the rate for a surface defined as stable. Symbols are identified in Table 1.

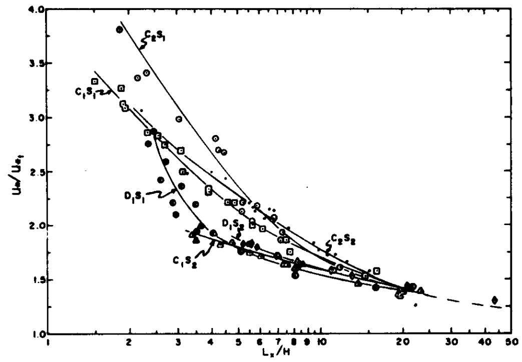

FIG. 2 Critical friction velocity ratio (u_*/u_{*_t}) as related to the CSBR (L_x/H) for all data. Symbols are defined in Table 1.

we obtained a longitudinal, turbulence-intensity profile at the same location we obtained mean windspeed profiles. The pitot-static tube readings were corrected for the effects of turbulence by procedures developed previously (Lyles et al 1971).

The mean velocity-profile parameters (Z_o, D, u_*) were obtained from this equation, applicable to adiabatic flows in the lower 10 to 20 percent of the boundary layer:

$$\frac{\bar{u}_z}{u_*} = \frac{1}{k} \ln\left(\frac{Z - D}{Z_o}\right) \ldots\ldots\ldots\ldots [1]$$

where $\bar{u}_z$ is mean windspeed at height Z above some reference plane; u_*, 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, von Karman's constant (0.4); D, an effective roughness height; and Z_o, a roughness parameter.

EXPERIMENTAL DATA AND OBSERVATIONS

Sand-loss rates approached zero asymptotically with time. An average of about 21 hr was required for the loss rate to reach about 0.05 g per min (extremes were 5 and 72 hr). Generally, less time was required for larger roughness elements and larger particle sizes. The time for stabilization also was related to the difference between actual and threshold windspeed at the beginning of a run and, of course, to sand-loss rate when a run was terminated.

After a given surface had stabilized at some free-stream windspeed, we collected a surface sample to compare its particle size distribution with that of samples transported from the test area during surface stabilization. The surface samples contained more large particles than did the transported samples, indicating some surface "armoring," even though all particles were of erodible size (Table 2).

Friction velocities expressed in dimensionless form over surfaces considered stable versus the CSBR are shown in Fig. 2; u_{*_t} (threshold friction velocity for the erodible particles) equalled 21.64 and 31.14 cm per sec for d_1 and d_2, respectively. We call u_*/u_{*_t} the critical friction-velocity ratio because, if exceeded, erosion would begin. u_* is the total friction velocity existing when a surface stabilizes at a given free-stream velocity. Obviously, the CSBR is not constant for a given friction velocity, regardless of the size and proportion of nonerodible particles. Apparently, using the ratio of distance between nonerodible elements to their height to define a stable surface does not adequately describe the numerous sizes and distributions that could occur. Consequently, we searched for additional dimensionless parameters that characterize the roughness-element geometry and could correlate all the data. Some of the parameters considered and their correlation coefficients are presented in Table 3. Also included in this table are correlations for the drag coefficient, C_d, which was computed from:

$$C_d = 2u_*^2/\bar{u}_z^2 \ldots\ldots\ldots\ldots\ldots [2]$$

where u_z is the mean windspeed at Z = 1.6H; H, the average roughness-element height. The reference elevation for mean windspeed was chosen because Marshall (1970) had used equation [2] to characterize eroison potential. He reported that no regional erosion would occur when $C_d \geqslant 0.0147$. Terms not identified in Table 3 are:

N = number of roughness elements in total area A_t

A_s = silhouette area of a single roughness element

A_p = plan-view area of a single roughness element.

The dimensionless term, NA_p/A_T, is the proportion of total surface area covered by the nonerodible roughness elements and will be noted hereafter as A_c.

Selected regression equations (using

TABLE 2
ARMORING OF SURFACE DURING STABILIZATION

Particle-size range, mm	d_{50}*, mm		Percent finer at d_1 = 0.25 mm; d_2 = 0.50 mm	
	Surface	Sediment	Surface	Sediment
0.15 – 0.42 (d_1)	0.29†	0.26	21	39
0.42 – 0.59 (d_2)	0.52†	0.49	36	51

*50 percent finer than size indicated.
†Surface significantly larger than sediment at 1 percent probability level.

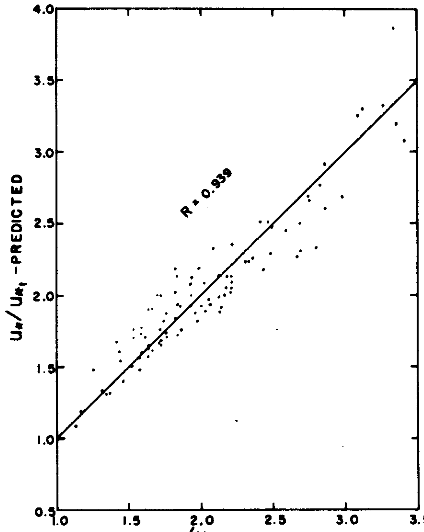

FIG. 3 Measured values of u_*/u_{*t} compared with those predicted by equation [9]. All data.

stepwise procedures with 4 percent F level for entering parameters) for the cylinder, sphere, and combined data include:

Cylinders

$$u_*/u_{*t} = 1.357 + 3.730\,(H/L_x);\quad r = 0.9155 \quad [3]$$

$$u_*/u_{*t} = 0.8043 + 5.743\,(H/L_x) - 3.441\,(H/L_x)^2 + 28.05\,A_c - 288.37\,A_c^2;\quad R = 0.9739 \quad [4]$$

$$C_d = 0.0051 + 0.025\,(H/L_x) + 1.571\,A_c - 61.43\,A_c^2 + 592.4\,A_c^3;\quad R = 0.9238 \quad [5]$$

Spheres

$$u_*/u_{*t} = 1.2096 + 3.069\,(H/L_x);\quad r = 0.9693 \quad [6]$$

$$C_d = 0.0095 + 0.0152\,(H/L_x) + 0.0789\,A_c;\quad R = 0.9839 \quad [7]$$

Combined (cylinders and spheres)

$$u_*/u_{*t} = 1.318 + 3.517\,(H/L_x);\quad r = 0.8965 \quad [8]$$

$$u_*/u_{*t} = 1.074 + 3.942\,(H/L_x) + 15.17\,A_c - 189.55\,A_c^2 + 543.41\,A_c^3;\quad R = 0.9395 \quad [9]$$

$$C_d = 0.0115 + 0.433\,(NA_s/A_T) - 1.990\,(NA_s/A_T)^2;\quad R = 0.9002 \quad [10]$$

Equations [9] and [10] are compared with measured experimental data in Figs. 3 and 4, respectively.

INTERPRETATIONS AND DISCUSSION

Some discussion of the parameters in Table 3 and equations [3] to [10] seems appropriate. The term, $1/NA_s/A_T)^{1/2}$, in row 2 of Table 3 was suggested by Marshall (1971) for describing the roughness array (distribution). Our data correlated poorly using this parameter.

Using the reciprocal of the CSBR defined by Chepil and Woodruff (row 3, Table 3), our data, especially the sphere data, correlated fairly well. As mentioned earlier, Chepil's original conclusions were based on this reciprocal parameter. Unfortunately, he later changed the definition to agree with standard wind-barrier protection terminology, apparently unaware that his original conclusions might be invalidated.

The only dimensional parameter considered, HNA_s/A_T (row 6, Table 3), was suggested by Lettau (1969) for determining the roughness parameter, Z_o. Any accurate equation for Z_o based on roughness-element geometry should correlate well with friction velocity. Although correlation was good, several other parameter combinations were superior.

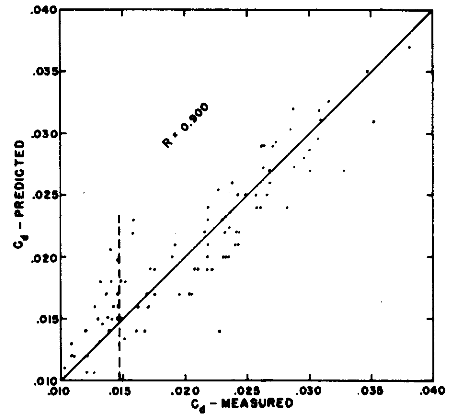

FIG. 4 Measured drag coefficients compared with those predicted by equation [10]. Vertical dashed line indicates values of C_d, as suggested by Marshall (1970), above which no regional erosion would occur.

Critical Friction Velocity Ratio

The critical friction velocity ratio, u_*/u_{*t}, was correlated best using polynominal or power functions of H/L_x and A_c. For simplicity, equation [8] could be used. For increased accuracy, equation [9] could be used. The range of values used in determining the regression equations was 0.002 to 0.668 for H/L_x and 0.0014 to 0.169 for A_c. During the study we determined values of U_* for H/L_x = 1.09, which we suggest as an upper limit for H/L_x. None of the equations should be extrapolated far beyond those ranges of values used in obtaining them. For example, in equation [4], $H/L_x \geq 2$ and small values of A_c will give negative values of u_*/u_{*t}! However, equations [8] or [9] will give positive values for all values of H/L_x. Note that

TABLE 3
SIMPLE OR MULTIPLE CORRELATION COEFFICIENTS BETWEEN STABLE FRICTION VELOCITY RATIO OR DRAG COEFFICIENT AND SEVERAL DIMENSIONLESS PARAMETERS DESCRIBING THE ROUGHNESS-ELEMENT GEOMETRY

Parameters considered*	Cylinders u_*/u_{*t}	Cylinders C_d	Spheres u_*/u_{*t}	Spheres C_d	Cylinders and spheres u_*/u_{*t}	Cylinders and spheres C_d
			r or R			
$(L_x/H)^1$	0.7802	0.5720	0.4224	0.3225	0.2913	0.2433
$1/(NA_s/A_T)^{1/2}$					0.3995	0.3718
$(H/L_x)^1$	0.9155	0.6388	0.9693	0.9521	0.8965	
$(H/L_x)^{1,2}$	0.9314	0.6749	0.9715	0.9525	0.9017	
$(NA_p/A_T)^{1,2}$	0.3328	0.6773	0.8809	0.9853		
$(HNA_s/A_T)^1$					0.8779	0.6791
$(NA_s/A_T)^{1,2,3}$	0.9505	0.9183			0.8880	0.9002
$(H/L_x)^1, (NA_p/A_T)^1$	0.9477	0.8625	0.9734	0.9839	0.9035	0.7892
$(H/L_x)^{1,2}, (NA_p/A_T)^{1,2}$	0.9739	0.9259	0.9812	0.9880		
$(H/L_x)^{1,2,3}, (NA_p/A_T)^{1,2}$	0.9744	0.9276	0.9828	0.9881		
$(H/L_x)^{1,2}, (NA_p/A_T)^{1,2,3}$					0.9470	0.8479
$(H/L_x)^1, (NA_p/A_T)^{1,2,3}$	0.9630	0.9238			0.9395	0.8373

*Exponents refer to the powers on the parameters included in the regression equations.

A_c cannot exceed 1.0 (that is, 100 percent of the area covered with nonerodible elements).

Drag Coefficient

Marshall's (1970) value of the overall drag coefficient above which no regional erosion would occur ($C_d \geqslant 0.0147$) appears to contain some margin of safety (Fig. 4). When determining the critical value of C_d, he assumed drag was negligible on the intervening surface among roughness elements. However, the intervening drag need only be reduced below the threshold for the erodible particle sizes in question. Therefore, our data suggest the critical drag coefficient could be lowered to $\geqslant 0.0104$.

Later, in a wind-tunnel experiment, Marshall (1971) made drag measurements of about 40 combinations of diameter-height ratios (d/H) and spacing-height ratios (L_x/H), using cylinders and hemispheres. To develop an equation for critical conditions based on the unobstructed drag coefficient and NA_s/A_T for various roughness elements, he partitioned the total drag, τ, into that due to the roughness elements, τ_r, and that due to the intervening surface, τ_s:

$$\tau = \tau_r + \tau_s \qquad [11]$$

From direct measurements of τ and τ_r, which indicated when τ_s approached zero, critical values of NA_s/A_T were determined. Using Marshall's roughness-element data for which $\tau_s \to 0$, we computed u_*/u_{*t} from our equation [9] (Table 4). Only three of the 13 roughness-element arrays appeared to be stable against natural winds; 8 resulted in u_*/u_{*t} values <2.5, which often could be exceeded by natural winds. For example, a u_*/u_{*t} value of 2.5 and the d_1 erodible-particle size could be reached with a free-stream velocity of about 755 cm per sec (16.9 mph).

How Surface Stabilizes

How nonerodible roughness elements control sand movement is illustrated in Fig. 5. The control process will be described with the aid of equation [11]. When the smooth sand-grain surface initially is exposed to the windspeed indicated, the total friction velocity or drag equals the drag on the intervening surface ($\tau = \tau_s$) because no roughness elements are exposed; that is, H = 0 and therefore drag due to roughness elements (τ_r) is also zero. As the surface erodes (exposing roughness elements), the total drag increases, the drag on the intervening surface decreases, and the drag on the roughness elements increases markedly. Erosion continues until drag on the intervening erodible particles decreases to the threshold for the particles in question ($\tau_s = \tau_t$). At that threshold, where movement ceases, the difference in total drag and the roughness-element drag is also equal to the threshold drag for the given particle-size range ($\tau - \tau_r = \tau_t$).

TABLE 4

VALUES OF u_*/u_{*t} COMPUTED FROM EQUATION [9] FROM CRITICAL—ROUGHNESS ELEMENT DATA OF MARSHALL (1971)

Cylinder diameter, cm	H/L_x	A_c	u_*/u_{*t}	τ_s, dynes per sq cm (Marshall)
2.54	0.1667	0.0160	1.933	0.41
5.08	0.1667	0.0490	2.093	0.29
7.62	0.1667	0.0872	1.971	0.08
1.27	0.4000	0.0218	2.906	- 0.08
2.54	0.2000	0.0218	2.118	- 0.54
2.54	0.5000	0.0872	3.285	- 2.73
5.08	0.2500	0.0872	2.300	- 0.67
5.08	1.0000	0.3487	14.159	0.41
7.62	0.2000	0.1105	1.962	3.90
7.62	0.3333	0.1442	2.328	----
7.62	1.0000	0.4418	30.689	----
12.70	0.2000	0.1964	2.004	0.61
12.70	0.5000	0.4006	20.050	----

Practical Considerations

Equation [9] has some practical implications. For example, values of u_*/u_{*t} below which no significant erosion would occur for several standing crop residues and plant heights are given in Table 5. If one used a design value of 5 for u_*/u_{*t}, corn populations would seldom be large enough to control erosion on highly susceptible soils, unless stalk residues were higher than 30.48 cm.

Because soybean stalks are clipped close to the soil surface, the number of standing stalks alone would not effectively control wind erosion on susceptible soils.

Apparently, 508 lb per acre of standing sorghum stubble 30.48 cm high or 87 lb per acre of wheat stubble 7.62 cm high would control erosion effectively (for the selected design value of u_*/u_{*t} = 5), assuming equidistant spacing of plants. Others have reported requirements of 3,500 to 4,800 lb per acre of standing sorghum stubble for loamy fine sands and 1,050 to 1,750 lb per acre of standing wheat stubble (Chepil et al 1961, Fryrear 1969, Woodruff et al 1972). We are not certain why amounts calculated by equation [9] differed so markedly from those previously reported. Noting that most studies on wheat have dealt with fairly tall stubble (25.4 cm or more), we think a partial answer is that stubble height effectiveness diminishes as height exceeds a certain value for a given spacing. That observation is supported by data of Siddoway et al (1965), who reported 291 lb per acre of standing wheat stubble reduced erosion to an insignificant amount when exposed to a friction velocity of 94.7 cm per sec. That friction velocity would be equal to a u_*/u_{*t} of 4.38 for our smallest particle-size range. If the 25.4-cm stubble height of Siddoway et al (1965) were reduced to 7.62 cm (the height we found to be effective), the quantity of stubble required would be 87.3 lb per acre, almost identical with our data in Table 5. Other factors to consider are: (a) cultivated crops are seldom, if ever, uniformly distributed over the surface, and (b) the regression equation may not be valid for extrapolations beyond the range of experimental roughness elements used to develop it.

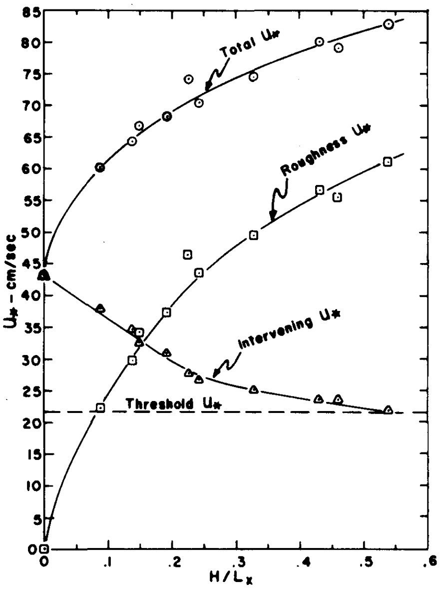

FIG. 5 How friction velocity or drag changes as a surface stablizes by exposing nonerodible roughness elements. Data are based on u_∞ = 1,300 cm sec; d_1 = 0.15 to 0.42 mm diameter; L_x = 3.491 cm; C_2 = 1.589 cm diameter in uniformly spaced diagonal arrays.

The relative influence of stubble height and number of plants on stopping erosion, and comparisons with results obtained by Siddoway et al (1965) are given in Table 6. Note the two comparisons with coarse sorghum; 1,209 lb per acre of 25.4-cm-high stubble would provide the same protection as 2,310 lb per acre of 9.4-cm-high stubble and indicates, within limits, that height is more important than number of plants per acre.

The importance of height of standing crop residues is emphasized by noting the protection provided by wheat stubble (87 lb per acre, 7.62 cm long) lying flat (uniformly distributed) on the surface. For the flat stubble, u_*/u_{*t} is 1.56, compared with 5.23 for the same amount of standing stubble.

One could also compute the number of soil aggregates or clods required to prevent erosion for design values of u_*/u_{*t} (Fig. 6). Assumptions in Fig. 6 are: (a) clod height (H) is equal to two-thirds of the diameter, and (b) clods are uniformly spaced. Calculations by Woodruff and Lyles (1967), based on Chepil's definition of the CSBR, indicate five times as many clods are required to give the same protection as the number computed from equation [9].

Our data suggest that equidistant spacing of plants (at high plant populations) would effectively control wind erosion if the stalks were left standing after harvest. Dungan (1946) attributed significant increases in corn yields in 2 of 7 years to equidistant spacing of single plants. However, in those tests, yields were above normal in 6 of the 7 years. Hoff and Medereski (1960) found corn yield increased 5 to 10 bu per acre when plants (at plant populations of 16,000 to 28,000 per acre) were spaced equidistantly. They suggested equidistant plant spacing increases shading of soil surface, conserves soil moisture, and improves use of solar energy. Such possible yield increases and protection against wind erosion should stimulate additional study of modifications in planting, harvesting, or other management techniques that would be required for equidistant-plant-spacing systems.

SUMMARY

We studied how nonerodible roughness elements of various sizes, shapes, spacings, and distributions control sand movement in a wind tunnel. We found the critical surface-barrier ratio (CSBR)—distance between nonerodible surface barriers divided by the height of barrier that will prevent wind from moving erodible particles—was not constant for a given friction velocity (regardless of size and proportion of nonerodible particles), as reported by other workers. However, regression equations relating the critical friction-velocity ratio, u_*/u_{*t}, to dimensionless parameters H/L_x and A_c correlated the data well. (u_* is the total friction velocity existing when a surface stabilizes at a given free-stream velocity; u_{*t}, the threshold friction velocity for a given particle-size range and specific gravity; H, average roughness element height; L_x, spacing between roughness elements in the flow direction; and A_c, the proportion of total surface area covered by roughness elements.)

In the process of surface stabilization (described in terms of partitioning total drag into drag on the roughness elements and drag on the intervening erodible surface, as shown in Fig. 5), total drag and roughness-element drag increased as particles eroded from the in-

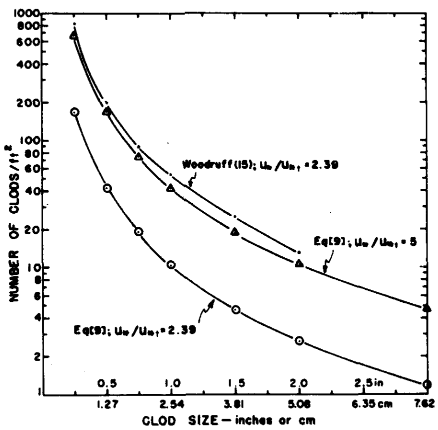

FIG. 6 Number of clods of different sizes required on the soil surface to protect against critical friction velocity ratios of 2.39 and 5.0. Earlier data of Woodruff and Lyles (1967) were based on a critical-surface-barrier-ratio equation.

TABLE 5

CRITICAL FRICTION-VELOCITY RATIOS (u_*/u_{*t}) BELOW WHICH NO SIGNIFICANT EROSION WOULD OCCUR FOR SEVERAL CROP RESIDUES AT SELECTED PLANT POPULATIONS AND HEIGHTS (STANDING)†

Crop	Populations, plants per acre	Height, cm	u_*/u_{*t}	Plant weight, lbs per acre
Sorghum	40,000	30.48	5.009	508
Sorghum	40,000	15.24	3.174	254
Wheat	720,000	30.48	17.693*	350
Wheat	720,000	15.24	9.385*	175
Wheat	720,000	7.62	5.231	87
Wheat	3,000,000	5.08	7.000*	243
Wheat	3,000,000	3.78	5.503	181
Corn	25,000	30.48	4.321	1,264
Corn	25,000	15.24	2.720	632
Corn	25,000	38.10	5.121	1,580
Corn	15,000	30.48	3.537	759
Soybeans	150,000	10.0	3.605	---
Soybeans	150,000	6.0	2.599	---
Cotton	40,000	30.48	4.950	---
Cotton	40,000	15.24	3.001	---

†Calculated values of u_*/u_{*t} assume the intervening surface is bare, all particles are 0.15- to 0.42-mm diameter sand, and plants are uniformly distributed.

*H/L_x values too far outside limits of equation [9].

TABLE 6
PLANT HEIGHTS (H) FOR VARIOUS STANDING CROP RESIDUES ABOVE WHICH NO SIGNIFICANT EROSION WOULD OCCUR. PLANT DATA AND FRICTION VELOCITY FROM SIDDOWAY ET AL. (1965)

Crop residue	Plants per acre	u_*, cm per sec	Siddoway H required, cm	Siddoway Residue weight, lb per acre	Equation [9] H required, cm	Equation [9] Residue weight, lb per acre
Wheat	720,000	94.7	25.4	291	6.1	70
Fine sorghum	137,600	94.7	25.4	1,249	13.1	644
Coarse sorghum	191,000	94.7	25.4	6,241	9.4	2,310
Coarse sorghum	37,000†	94.7	----	----	25.4	1,209

†Plants required using Siddoway's H of 25.4 cm.

tervening surface, exposing the roughness elements. When particle movement ceased for a given free-stream velocity, drag on the intervening surface had been reduced to the threshold drag, while total drag and roughness element drag had reached a maximum.

Practical results of the study, expressed in terms of the protection provided by various crop residues for several plant populations and heights, indicate much lower amounts of crop residues than reported by others are effective for a design value of 5 for u_*/u_{*t}, if the residues are standing and equidistantly spaced. The number of soil aggregates or clods required to protect against given critical-friction velocity ratios (u_*/u_{*t}) were presented.

Possible yield increases and protection against wind erosion suggest the need for additional study of modifications in planting, harvesting, or other management techniques required for equidistant-plant-spacing systems.

References

1 Bagnold, R. A. 1943. The physics of blown sand and desert dunes. William Morrow & Co. 265 p.

2 Chepil, W. S. 1950. Properties of soil which influence wind erosion: I. The governing principle of surface roughness. Soil Sci. 69:149-162.

3 Chepil, W. S. 1958. Soil conditions that influence wind erosion. USDA Tech. Bull. No. 1185.

4 Chepil, W. S. 1944. Utilization of crop residues for wind erosion control. Sci. Agr. 24(7):307-319.

5 Chepil, W. S. and N. P. Woodruff. 1963. The physics of wind erosion and its control. Advances in Agron. 15:211-302.

6 Chepil, W. S., N. P. Woodruff, and F. H. Siddoway. 1961. How to control soil blowing. USDA Farmers' Bull. No. 2169.

7 Dungan, G. H. 1946. Distribution of corn plants in the field. Jour. Amer. Soc. Agron. 38:318-324.

8 Fryrear, D. W. 1969. Reducing wind erosion in the Southern Great Plains. Texas Agr. Exp. Sta. MP-929.

9 Hoff, D. J. and J. H. Medereski. 1960. Effect of equidistant corn plant spacing on yield. Agron. Jour. 52:295-297.

10 Lettau, H. 1969. Note on aerodynamic roughness-parameter estimation on the basis of roughness-element description. Jour. Appl. Meteorol. 8:828-838.

11 Lyles, Leon, L. A. Disrud, and R. K. Krauss. 1971. Turbulence intensity as influenced by surface roughness and mean velocity in a wind-tunnel boundary layer. TRANSACTIONS of the ASAE 14(2):285-289.

12 Marshall, John K. 1970. Assessing the protective role of shrub-dominated rangeland vegetation against soil erosion by wind. Proc. XI International Grassland Congress, p. 19-23.

13 Marshall, John K. 1971. Drag measurements in roughness arrays of varying density and distribution. Agr. Meteorol. 8(4/5):269-292.

14 Siddoway, F. H., W. S. Chepil, and D. V. Armbrust. 1965. Effect of kind, amount, and placement of residue on wind erosion control. TRANSACTIONS of the ASAE 8(3):327-331.

15 Woodruff, N. P. and Leon Lyles. 1967. Tillage and land modification to control wind erosion. Proc. Tillage for Greater Crop Production published by ASAE, p. 63-67, 70.

16 Woodruff, N. P., Leon Lyles, F. H. Siddoway, and D. W. Fryrear. 1972. How to control wind erosion. USDA Agr. Inf. Bull. No. 354, 22 p.