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PRESENTATION

WIND EROSION: EMISSION RATES AND TRANSPORT CAPACITIES ON ROUGH SURFACES

by

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SUMMARY:

As part of a series of wind tunnel studies for WEPS, emission of loose sand from among simulated clods was investigated. Threshold velocities, saltation transport capacity coefficients, and emission rate coefficients are reported. Theory to predict surface armoring by clods in response to loose soil emission was also derived.

KEYWORDS:

Wind erosion, saltation, armoring.

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INTRODUCTION

A modeling team in the United States Department of Agriculture is developing technology to replace the current wind erosion equation (Woodruff and Siddoway, 1965) with a computer model, dubbed WEPS for Wind Erosion Prediction System. WEPS simulates wind erosion, as well as the weather, hydrology, soil, tillage, and biomass conditions that control wind erosion (Hagen, 1991a). A field measurement program is also being carried out at several locations to validate WEPS (Fryrear, et.al, 1991).

In the erosion submodel of WEPS, the soil moving in the saltation and creep transport modes is modified by a series of sources and sinks, using the principle of mass conservation applied to a control volume (Figure 1). The sources are emission of loose aggregates from among the large clods and abrasive breakdown of clods and crust to wind-erodible size from impact of saltating aggregates (Hagen, 1991b). The sinks are trapping (deposition) of saltation and creep in sheltered areas and suspension of fine particles through the top of the control volume.

Parameters for the WEPS erosion submodel are being developed in a series of wind tunnel studies. This study was undertaken to determine parameters to describe the emission of loose aggregates from among the large immobile clods. In general, the literature on emission and transport of loose aggregates deal only with surfaces composed of all-erodible aggregates (Bagnold, 1941; Greeley and Iversen, 1985; Anderson and Haff, 1988). Studies with non-erodible elements have generally used defined elements, such as spheres, and focused mainly on the change in threshold friction velocity caused by the elements (Lyles, Schrandt, and Schmeidler, 1974; Gillette and Stockton, 1989).

The objectives of this study were to determine emission rate coefficients, transport capacity coefficients, and total emission loss possible for cloddy surfaces with random roughness projections.

ANALYTICAL EQUATIONS

Saltation Transport Capacity

Because accurate measurements of saltation discharge under equilibrium flow conditions are difficult to obtain, a number of equations have been proposed to describe saltation transport capacity. One of the earliest was that of Bagnold (1941), which for erodible sand had the form

$$\frac{q_c g}{\rho u_*^3} = C\left(\frac{D_p}{D_{po}}\right)^{(1/2)} \qquad (1)$$

where

q_c = saltation discharge transport capacity, M L^{-1} T^{-1},
g = acceleration of gravity, L T^{-2},
ρ = air density, M L^{-3},
u_* = friction velocity, L T^{-1},
D_p = particle diameter, L,
D_{po} = reference particle diameter, 0.025 mm, and
C = a dimensionless coefficient.

Bagnold (1941) also found that the transport capacity could double for mixed erodible particles compared to particle beds of uniform size; therefore, C was not a constant.

Bagnold's formula did not explicitly consider the surface threshold friction velocity, so a number of variations have been proposed (Greeley and Iversen, 1985). Because surface threshold friction velocity has a large impact on the behavior of rough surfaces, an equation suggested by Lettau and Lettau (1978) was selected for testing in this study. The selected equation has the form

$$q_c g/\rho u_*^3 = C(1 - u_*/u_{*t}) \tag{2}$$

where

u_{*t} = surface threshold friction velocity, L T^{-1}, and

the other variables are as previously defined.

Emission Rate

On surfaces composed of all-erodible particles, the distance required to reach transport capacity is only a few meters. Even on non-homogeneous, but highly erodible sandy fields, the upwind fetch needed to reach saltation transport capacity has been measured at 30 m (Chepil, 1959). However, when large aggregates cover part of the surface, the emission rate is restricted and the fetch needed to reach transport capacity may be hundreds of meters. In this case, it is of great practical importance in the modeling of wind erosion to develop predictions for emission rates for surfaces where emission is restricted.

For simple, bare, erodible, field surfaces, Stout (1991) proposed an equation of the form

$$dq/dx = B\ (q_c - q) \tag{3}$$

where

q_c = saltation discharge along the wind direction, M $L^{-1}T^{-1}$,
x = horizontal distance along the wind direction, L, and
B = emission rate coefficient, L^{-1}.

Integration of the preceding equation gives

$$q_o = q_c(1 - e^{-BL}) \tag{4}$$

where
q_o = saltation discharge at distance L, $M\ L^{-1}T^{-1}$, and
L = horizontal distance downwind from non-erodible boundary.

Stout (1991) found by varying B, that the preceding equation provided a good fit to field experimental data on a highly erodible field, where the bulk of the saltating particles came from emission of loose soil. He further suggested that the coefficient B might be related to general field erodibility. However, other work has demonstrated that the abrasion loss from clods and crust obey other relations (Hagen, 1991b). Hence, in this study B was defined only as an emission rate coefficient for loose soil.

Total Emission Loss

In addition to rate of emission loss, the changes in surface condition as a result of emission are also of interest. As the erodible particles leave the surface, the soil surface becomes armored with immobile clods which can only be eroded by abrasion. If abrasion loss is small, such as at the upwind side of a field, the surface will stabilize under a given wind speed.

The change in surface clod cover caused by removing the saltation and creep-size particles can be described by the following equation:

$$\frac{dS}{dZ} = A_S \frac{(T - S)}{(T - I)} \tag{5}$$

where
S = surface clod cover, L^2,
T = total surface area, L^2,
Z = depth below initial soil surface, L,
A_s = plane projected surface area of clods per unit depth, L^2,
I = area of clods at level Z, occupied by clods whose tops are at a higher level, L^2.

Integrating the preceding equation to depth Z gives

$$T - S = (T - S_o)\, e^{-A_s Z/(T - I)} \tag{6}$$

Volume, V, of soil removed without undermining any surface clods is then given by

$$dV = (T - S)\, dZ \tag{7}$$

and again integrating to depth Z gives

$$V = \frac{(T - S_o)\ (T - I)}{A_S}\left(1 - e^{-A_s Z/(T - I)}\right) \tag{8}$$

where

S_o = is the area of clod cover on the initial surface. Thus, for any depth of soil removal Z, the two preceding equations can be used to calculate resultant surface clod cover, S, and volume of removal, V.

EXPERIMENTAL PROCEDURES

Saltation discharge transport capacities and emission rates for a series of random rough surfaces was measured in a wind tunnel. The wind tunnel facility is 1.52 m wide, 1.82 m high, and has a working section 16.46 m long. The tunnel is a recirculating push-type with a freestream longitudinal turbulence intensity of 1.7 percent. Airflow was generated by a 10-blade, variable pitch, axivane fan.

A random rough surface to simulate a cloddy soil surface was created on the downwind 12.5 m section of the tunnel floor. To avoid abrasion of the surface, a layer of simulated commercial rock (buildex) was used instead of soil clods. The maximum diameters through the centroid of the rocks ranged from 6.4 to 76 mm. The shapes of the rock closely resembled that of clods with average measured ratios of least diameter to maximum diameter through their centroids of 0.44. The rock layer was then covered with a layer of sieved quartz river sand 0.29 to 0.42 mm in diameter.

Typical experimental steps followed for each surface were as follows: Freestream wind speed was raised 0.5 m/s above the initial surface saltation threshold until a new surface stabilized by exposing some of the buried rocks to shelter the sand in the intervening spaces. Then, at two wind speeds (threshold velocity of the new surface and at 2 m/s less than threshold), profiles were measured in the boundary layer of mean wind speed using pitot-static tubes and turbulence intensity using a hot-wire anemometer. The wind speed profile data in the lower portion of the boundary layer were analyzed to determine the aerodynamic roughness parameters for the test surface as defined by the log-law wind speed profile (Panofsky and Dutton, 1984). The parameters calculated were the aerodynamic roughness length and the displacement height.

Next, two vertical slot saltation catchers were installed at the downwind end of the tunnel and a loose sand bed was installed upwind from the rock test surface. Transport capacity of the wind to move saltating particles across the stabilized rock surface was then measured during 90 second test runs at freestream wind speeds of one and two m/s above the threshold wind speed. The test runs were kept short to avoid significant changes in the stabilized test surface. After each run, sand trapped in the catchers was collected and weighed. Average freestream wind speed also was measured during each run.

Finally, the upwind sand bed was removed and the 90 second test runs were repeated. Sand trapped in the catchers was again weighed and an average emission rate coefficient for the test surface was calculated using equation 4.

The testing sequence of raising the surface threshold wind speed and then determining aerodynamic roughness parameters, saltation discharge transport capacity, and emission rate coefficients was repeated a number of times for each initial rock test surface.

RESULTS AND DISCUSSION

Saltation Transport Capacity

The dimensionless saltation transport coefficient was computed from the saltation discharge trapped in the downwind catchers for 6 levels of surface roughness. The aerodynamic roughness of the surfaces with exposed rock, ranged from 0.5 to 3.0 mm, and the threshold friction velocities ranged from 0.55 to 1.0 m/s (Figure 2). The initial, slightly-rippled sand surface had an aerodynamic roughness of .03 mm and threshold friction velocity of 0.26 m/s.

The transport coefficient of equation 2 increased with initial sand removal from the test bed and then remained nearly constant until aerodynamic roughness reached about 2.8 mm at a threshold friction velocity of 0.91 m/s (Figure 3). The initial increase in the coefficient was probably caused by increasing rock cover, to the point where incoming grains no longer struck the intervening sand surface. This behavior is also in agreement with the observations of Bagnold (1941). A further increase in the transport coefficient was measured at the 3.0 mm roughness and 0.97 m/s threshold friction velocity. This observation needs further investigation, but may result from the high test wind speeds causing the saltating grains to jump to the upper portion of the boundary layer.

Overall, the experimental results show that as the surface becomes armored with rock or large aggregates, the transport coefficient increases. After the surface reaches a certain level of armoring, the coefficient then remains nearly constant for a wide range of threshold windspeeds. Further analysis of the surface cover and surface roughness at the point of transition to a constant coefficient are planned.

Emission Rate Coefficients

Emission coefficients were computed for 8 test surfaces using the measured downwind saltation discharge (Figure 4). While there was considerable scatter in the data, the mean emission coefficients exhibited a steady decrease as the surfaces became armored with rock. The initial sand surface attained saltation transport capacity within a few meters. However, calculations using the emission coefficients show the roughest 3 surfaces would need about 167 to 230 m of downwind fetch to attain 99 percent of transport capacity.

Total Emission Losses

Numerical results from equations 6 and 8 were calculated for soil mixtures containing 3 levels of cloddiness (5, 10 and 15 percent by volume) using 2 size ranges of non-erodible clods (0.84 to 6.4 mm and 6.4 to 12.8 mm diameter). The mass of loose, erodible size soil removed from among the clods, was calculated as a function of increase in clod surface cover (Figure 5).

The two size ranges of clods selected probably represent the boundary conditions for practical field cases. However, the results illustrate that the amounts of loose soil which must be emitted to reach a given level of surface clod cover may vary considerably.

Under test conditions using a constant friction velocity and single clod size range, one would expect the final surface clod cover and surface roughness to approach a constant value. Further, the final values should be constant, irregardless of the initial proportion of clods in the mixture.

Chepil (1951) reported emission losses from tunnel trays using initial mixtures of 5, 10, and 15 percent clod by volume as shown in Figure 5. His measured emission losses for a friction velocity of 0.61 m/s are plotted on the theoretical curves. The experimental results tend to cluster in a small range of final clod cover. The largest clod-size range probably produced the roughest surface, so the clod cover needed to provide a stable surface tended to decrease as clod size increased.

Further analysis of the present data sets are needed to determine the level of cover attained by other friction velocities. Nevertheless, the analytical approach embodied in equation 5 appears to be useful for predicting surface clod cover changes in response to emission of loose soil.

SUMMARY AND CONCLUSIONS

In this study, emission of loose sand by wind from among simulated clods was investigated in a wind tunnel facility. As sand was removed, both the aerodynamic surface roughness and threshold friction velocities increased. The saltation discharge threshold friction velocities increased. The saltation discharge transport capacity coefficients initially increased, but then remained nearly constant for a wide range of increases in surface roughness. The latter effect was probably caused by the surface becoming armored with rocks to the point where the saltating particles struck only surface rocks and not the intervening sand.

The emission rate coefficient, i.e., the rate at which saltation discharge increases toward transport capacity, asymptotically decreased as surface roughness increased. The data set will be further analyzed to relate the surface rock cover and roughness to the emission coefficients.

Past experiments show, total amounts of loose, erodible soil which can be emitted depend on both wind speed and surface-layer aggregate size distribution. A theoretical equation was developed to predict the effect of loose soil removal on surface armoring with immobile clods of various size ranges. Comparison with measured values suggests that erodible surfaces exposed to a constant friction velocity approach similar clod covers at stability, irregardless of the initial volume fraction of clods in the soil mixture. The final clod cover at stability also likely varies with the size distribution of clods.

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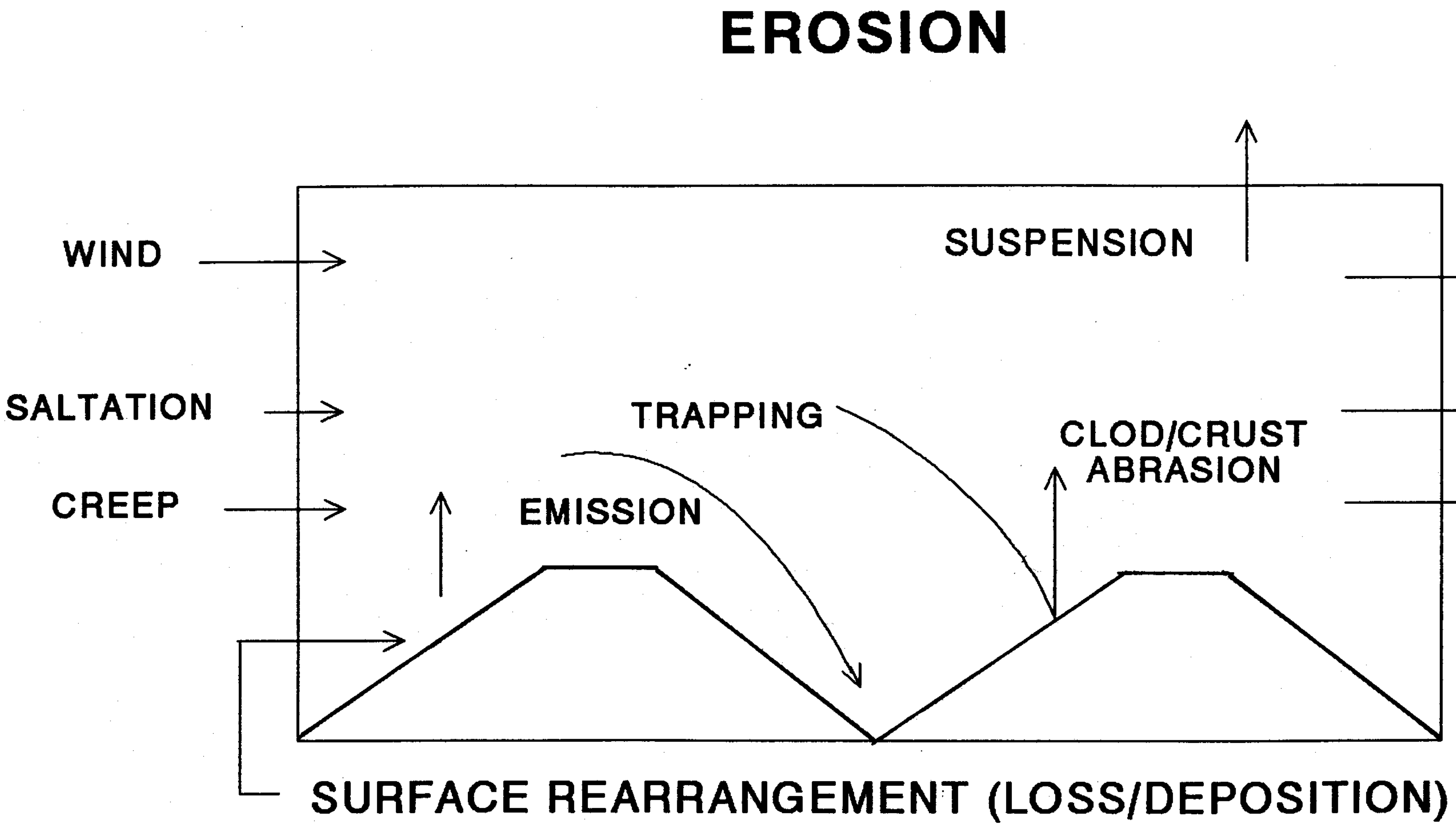

Figure 1. Schematic of an erosion submodel control volume illustrating conservation of mass of saltation and creep along with sources (emission of loose soil and abrasion of clods/crust) and sinks (suspension and trapping).

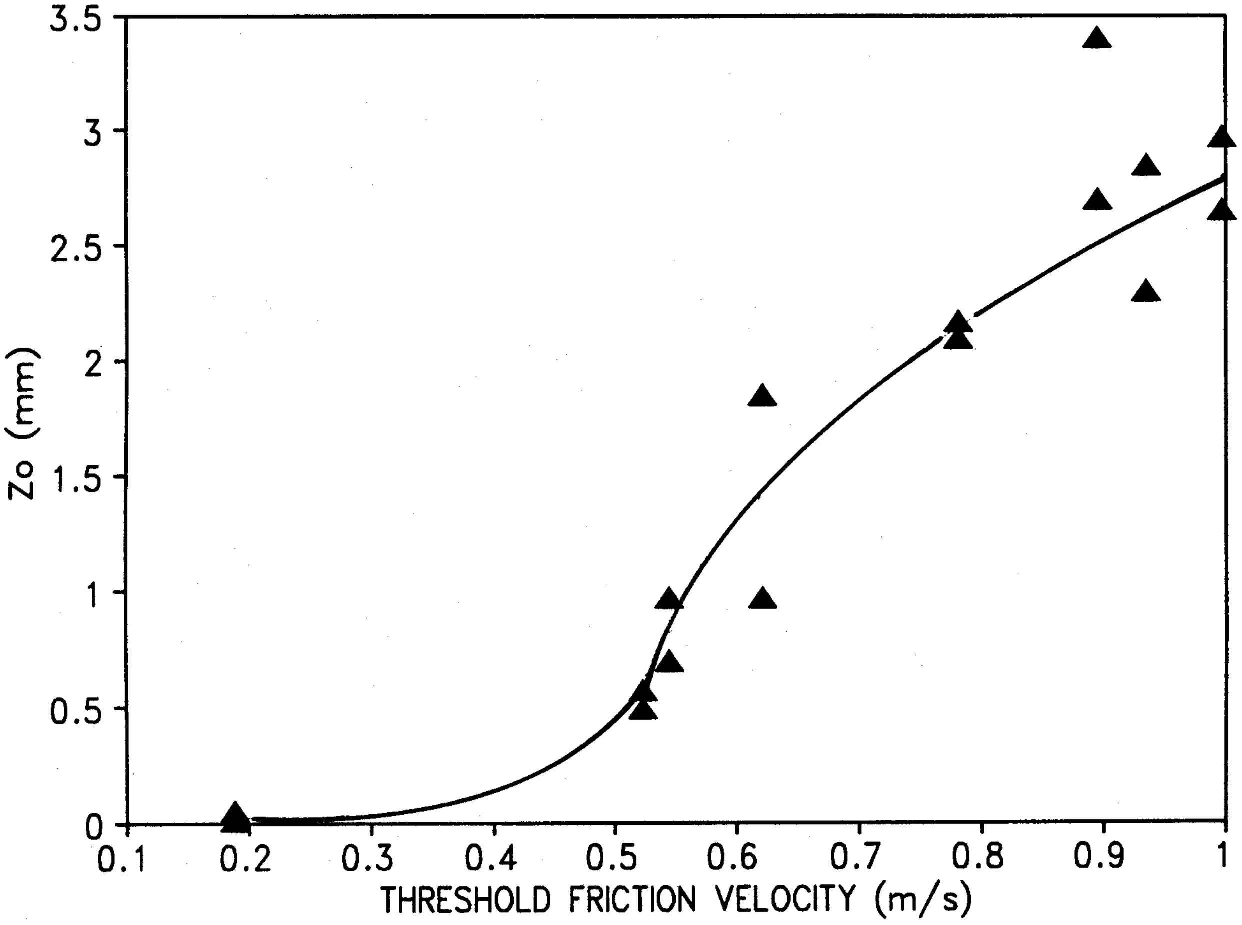

Figure 2. Surface aerodynamic roughness lengths as a function of surface threshold friction velocities.

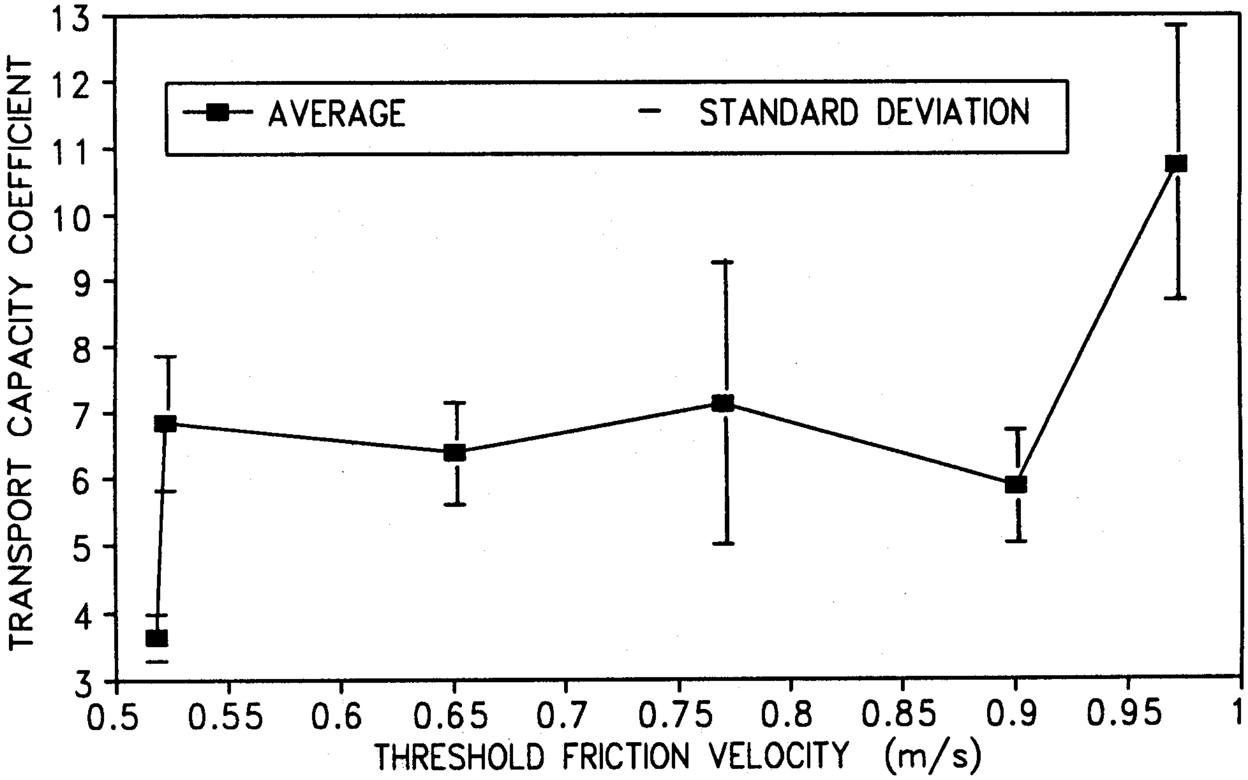

Figure 3. Mean and standard deviations of surface transport capacity coefficients as a function of surface threshold friction capacities.

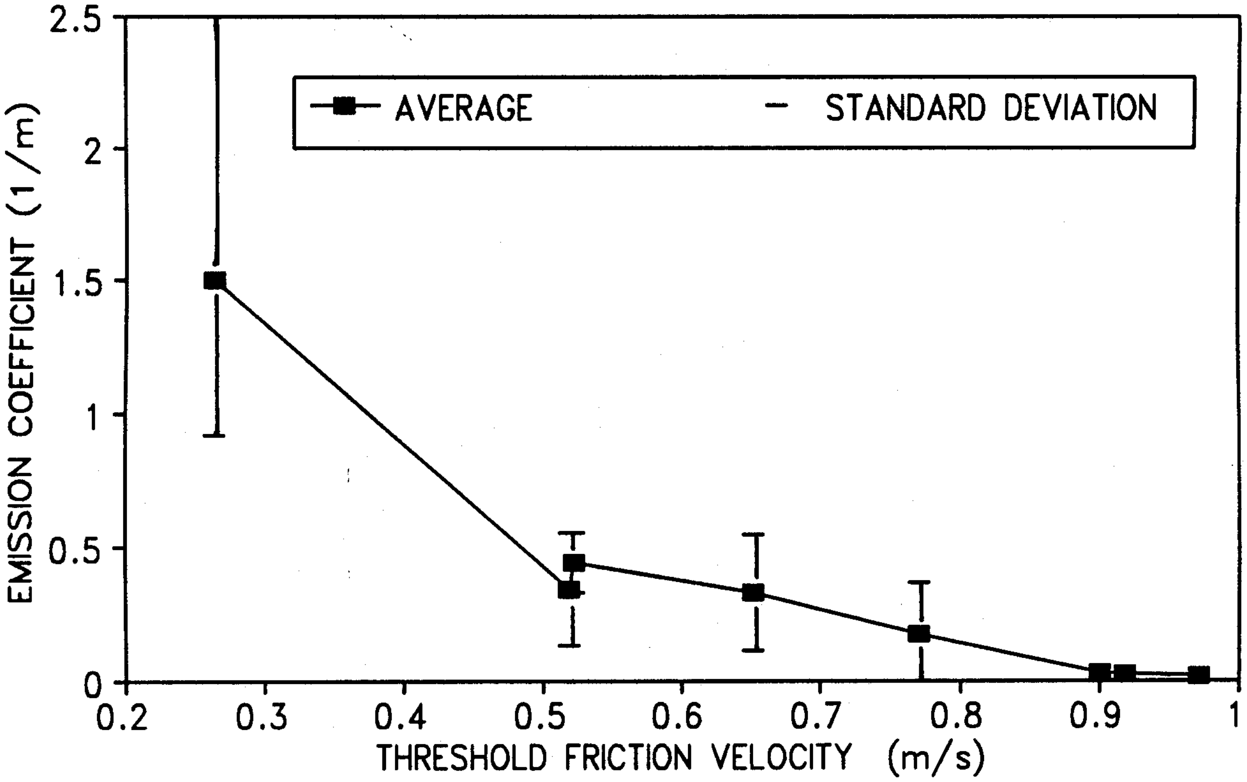

Figure 4. Mean and standard deviations of surface emission rate coefficients as a function of surface threshold friction velocities.

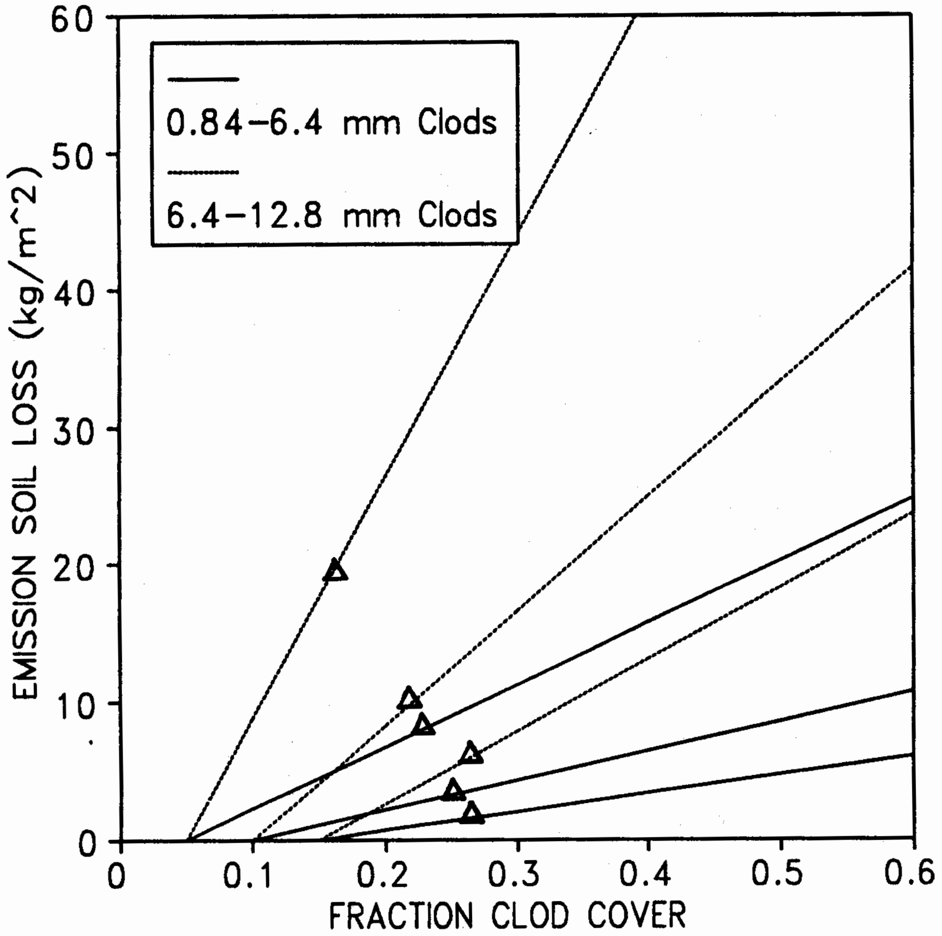

Figure 5. Lines represent theoretical emission loss as function of surface clod cover for two size ranges of clods. Triangles are measured emission losses (Chepil, 1951) with 5, 10, or 15 percent clods by volume in the initial mixture and a friction velocity of 0.61 m/s.