*This paper was peer-reviewed for scientific content.*
*Pages 742-746. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds). 2001. Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.*

# Assessment of Wind Erosion Parameters Using Wind Tunnels

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## ABSTRACT

**Assessment of wind erosion parameters applicable to the field scale using wind tunnels requires attention to both scaling laws and matching of nondimensional parameters. Proper upwind development of the boundary layer flow and meeting the Froude number criterion are especially important in studies involving saltation of aggregates in the wind stream.**

**Empirical wind erosion prediction models frequently use factors, called soil loss ratios, to represent the ratio of soil loss from a protected surface and a defined reference (usually highly erodible) surface. These ratios often are determined in wind tunnel tests but must be correlated to field wind erosion measurements before application. In addition, the ratios also are highly dependent on the tunnel wind speed used in the tests. Recent research has identified most of the critical physical parameters that control field-scale wind erosion. An alternative to measurement of soil loss ratios is to use wind tunnels to directly measure these physical parameters and apply them in physically based models. These parameters include the erosion threshold friction velocity, the saltation/creep transport capacity, the emission rate coefficient for loose soil, the abrasion rate coefficients for clods/crust, and the breakage rate coefficient of saltation/creep aggregates to suspension size. These parameters, along with the aggregates size distribution created by various processes, determine the downwind soil discharge in the saltation/creep and suspension transport modes. In general, one needs a relatively long wind tunnel, an upwind abrader feeder, wind speed measuring transducers, various surface materials, and specialized soil catchers to obtain downwind mass and size distribution of the soil discharge.**

## INTRODUCTION

During wind erosion, soil aggregates move in three modes of transport that generally are segregated by the size of aggregates. Creep-size aggregates (0.84 to 2.0 mm diameter) roll along the surface driven by saltation impacts and wind forces. The saltation-size aggregates (0.10 to 0.84 mm diameter) hop along the surface, whereas aggregates of suspension-size (< 0.10 mm diameter) move above the eroding surface and rarely impact it. Obviously, as wind speed, aggregate density, and saltation/creep load change, the aggregate sizes in each transport mode also may vary. Wind tunnels often are used to investigate the physics of soil entrainment and transport by wind erosion for conditions on earth (Bagnold, 1943; White, 1996), as well as on other planets (Greeley and Iverson, 1985).

The simplest wind erosion system consists of loose, dry, sand particles of uniform size and density moving in saltation/creep transport. For this system, considerable progress has been made both in understanding the physics and modeling its behavior (Anderson, Sorensen, and Willetts, 1991). Nevertheless, the response of sand flux to turbulent gusts (Butterfield, 1998) surface moisture, and surface evolution during erosion (Al-awadhi and Willetts, 1998) all require further investigation.

Typical, eroding, agricultural soil systems are more complex than sands. Some causes for the complexity include presence of a wide range of aggregate sizes, abrasion of immobile clods/crusts, breakage of the moving saltation/creep to suspension size, trapping of moving soil by vegetation or microrelief, and vegetation effects on airflow. Because of the complexity, most models of wind erosion for agricultural systems typically have been empirical (Woodruff and Siddoway, 1965; Fryrear et al., 1994 ).

Recently, a physically based model has been developed that includes equations and parameters designed to respond to many of the complexities in typical eroding agricultural fields (Hagen, et al., 1998). In this approach, separate, linked equations for the saltation/creep and suspension components were developed based on conservation of mass to predict downwind soil discharge. However, research is still needed to fully quantify the parameters that control wind erosion in agricultural systems, and wind tunnels can play an important role. The objectives of this report are to present brief overviews of: a) some relevant scaling laws when wind tunnels are used to determine erosion parameters for field-scale applications, b) past methodology used to determine soil loss ratios for empirical models, and c) new methodology to obtain parameters for physically based wind erosion models.

### Wind Tunnel Scaling for Erosion Experiments

When a wind tunnel is used, devices usually are installed in the upwind air stream to prepare the flow for the intended tests. A typical sequence of devices for wind erosion tests includes one or more screens to promote flow uniformity and decrease longitudinal turbulence, followed by a honeycomb to decrease lateral turbulence (Rae and Pope, 1984). Next, spires extending from the floor often are used to generate turbulence and increase the initial boundary layer

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depth. Downwind from the spires, various scales of roughness elements are used to further promote an equilibrium boundary layer with the desired turbulence intensity. Overall, mean power-law velocity profiles are desirable in the wind tunnel (wt) boundary layer to simulate a full-scale (fs) boundary layer (Snyder, 1972):

$$\frac{U_{wt}}{U_{fs}} = (\frac{Z_{wt}}{Z_{fs}})^{a} \tag{1}$$

where U is wind speed, Z is height above the surface, and 'a' is a constant.

It also is desirable to simulate the outdoor turbulence intensity level and turbulence energy spectra. Spires often can be used to generate the desired turbulence levels as well as shorten the 10 to 20 m down wind boundary layer development length that usually is needed.

One also must consider how the modeled system conforms to the scale of the outdoor system. There are three possibilities. One may have a true, or at least adequate, model. Alternatively, one may have a distorted model that requires correction of the predicted results. Finally, there are several cases where matching the required scales in the wind tunnel is extremely difficult For example, the tunnel does not simulate the scale of lateral turbulence in the atmosphere, so testing crops with rows parallel to the wind flow presents challenges. Similarly, one cannot simultaneously match both the saltation and dune scales, so simulating a multi-dune system in the tunnel does not appear feasible (White, 1996). In this report, we shall consider only true or adequate models.

To ensure models that are adequate, however, one still must match a series of nondimensional boundary conditions for similitude between outdoors and the wind tunnel. One must keep the tunnel model in the lower 20 percent of the boundary layer, unless the full-scale system extends further into the boundary layer. In this case, one must match the scales exactly between the tunnel and atmosphere. In addition, simulated wind barriers should meet Jensen's roughness criterion (Jensen, 1958) between the full scale (fs) and wind tunnel (wt), which can be expressed as:

$$(\frac{Z_o}{H})_{fs} = (\frac{Z_o}{H})_{wt} \tag{2}$$

where $Z_o$ is aerodynamic roughness length and H is characteristic height of the model. A barrier model also must occupy less than 10 percent of the tunnel cross-section to prevent flow blockage effects.

To ensure uniform longitudinal surface shear stress in the tunnel, one should maintain zero longitudinal pressure gradient. An adjustable wind tunnel ceiling that allows the tunnel cross-section to increase downwind is a common technique used to achieve this requirement.

For proper simulation of saltation in the wind tunnel, the Froude number (F) criterion should be met (White and Mounla, 1991). This criterion can be expressed as

$$F = \frac{U^2}{g\,H} < 10 \tag{3}$$

where U is upwind uniform wind tunnel velocity, g is acceleration of gravity, and H is wind tunnel height. High wind speeds in low-height tunnels readily violate the Froude criterion.

## Soil Loss Ratios

The soil loss ratio (SLR), also called relative erodibility, measured in wind tunnel experiments often has been used to derive parameters for empirical agricultural wind erosion prediction models (Fryrear et al., 1994; Woodruff and Siddoway, 1965). In general, the SLR is calculated from the ratio of response of a test surface to that of a reference surface. However, both the test conditions and the measured surface response used to calculate the SLR have varied among experimenters. For example, in an early experiment to evaluate the effect of tillage ridges, SLR values based on total soil loss from test ridges were reported (Armbrust, Chepil and Siddoway, 1964). A later experiment, reported SLR values based on a rate of soil loss from test ridges (Fryrear, 1984). The SLR values based on rate of soil loss during some period and total soil loss generally will yield different results.

The condition defined as a reference surface also has varied. Loose, erodible sand usually has been the preferred reference surface for studies on vegetation effects where rate of soil loss was the measured variable (Lyles and Allison, 1981). In contrast, a surface with 60 percent mass fraction greater than 0.84 mm was defined as the reference when SLR values based on total soil loss for cloddy surfaces were reported (Chepil, 1958).

In recent field experiments using a portable wind tunnel, the reference surfaces were established by removing the residue and smoothing the test plots surfaces with a garden rake (Horning, et al., 1998). The SLR values then were determined for various levels of flat residue cover and surface roughness. In that field study, a limited amount of saltation-size abrader also was introduced at the upstream end of the tunnel during the tests.

The SLR values also vary with the test wind speed. Some authors average the SLR values for several wind speeds (Horning, et al., 1998), while others use a single fixed test wind speed (Lyles and Allison, 1981).

Despite their popularity, direct physical interpretations of SLR values for field scale erosion are lacking. Hence, the application of SLR values to the field has been through the use of correlations to measured field soil losses. As a result, the SLR procedure must rely on obtaining field-scale measurements of wind erosion for a wide range of conditions to provide useful results.

Some of the problems in directly interpreting an SLR value for field-scale erosion are illustrated by a schematic of a typical application where a single SLR is applied over a range of wind speeds to a low population of standing residue stalks (Fig. 1). The product of the constant SLR and the reference field discharge provides a simple prediction of erosion over the range of wind speeds. However, the physical data suggest that the main effect of the standing residue is to raise the threshold velocity at which soil begins to move (Hagen, 1996). Hence, application of the SLR prediction tends to overestimate erosion at low wind speeds and underestimate it at high wind speeds. Of course, the

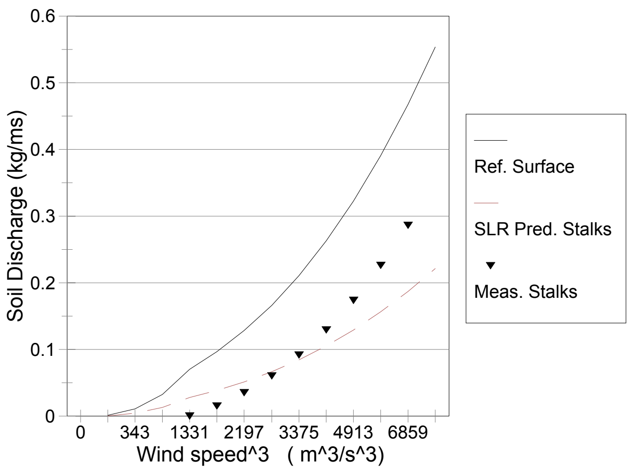


**Figure 1. Schematic of soil discharge from bare, loose erodible surface (reference), and thesame surface with standing residue stalks (measured) compared to predicted response obtained by selecting a single SLR value to represent the eroding system over a range of wind speeds.**

over and under estimates may balance to give a correct erosion estimate over some period. However, maintaining such a balance over a wide range of seasons and sites may be difficult.

## Direct Measurement of Erosion Parameters

Wind tunnels may be most useful in wind erosion research when applied to directly quantify the parameters that control wind erosion processes on a field scale. A further advantage is than they can be used to study individual processes that generally occur simultaneously in the field. Applying tunnels in this way should permit prediction of erosion directly from models that use the measured parameters, without the need for correlation to field measurements to establish relationships. This improves experimental efficiency, because undertaking numerous field studies is expensive and thus, rarely attempted. Nevertheless, field measurements are still needed for validation of prediction models. This is particularly true for fields that produce large amounts of suspended soil. Most of the critical erosion parameters now have been identified, and various tests can be used to quantify them. The measurement procedures that can be undertaken in a laboratory wind tunnel are discussed in the following sections.

## Threshold Friction Velocity

One of the critical parameters is the threshold friction velocity at which soil erosion begins. Soil movement is initiated when the most exposed, erodible aggregates begin to move and, as wind speed increases, general saltation finally occurs over the entire surface. Because a range of possibilities exists, how does one select a threshold value for practical application? As a guide, it may be useful consider how the threshold wind speed parameter is to be applied in models. Physically based models generally use the threshold friction velocity as a parameter in one of the saltation/creep transport capacity equations described by Greeley and Iversen (1985). Thus, one approach is to use the ratios of saltation/creep discharge from a tunnel at two or more wind speeds in the transport capacity equation of interest and solve for the unknown threshold velocity.

Because the tunnel discharge may not reach transport capacity over the tunnel length, one must make the further reasonable assumption that the fraction of the respective transport capacities achieved at both wind speeds is the same.

Measurements of the aerodynamic roughness, surface aggregate size distribution, and surface roughness also should be made on the same test surfaces. These data currently are lacking from most data sets reporting threshold velocities, except those with a uniform particle size. Many data sets are available for the latter test condition (Greeley and Iversen, 1985).

## Saltation/Creep Transport Capacity

Another parameter is the saltation/creep transport capacity of the test surface. For a surface composed mainly of loose, erodible soil, transport capacity usually can be reached within the length of a tunnel and, thus, sampled with a slot sampler at the tunnel outlet. However, without proper roughness length conditioning at the entrance to the tunnel working section, a smooth-to-rough transition can be caused by the entrainment of saltation-size aggregates and result in an overshoot of the transport capacity in a short tunnel, as described by Leys and Raupach (1991).

For surfaces partially armored with immobile elements, the transport capacity often cannot be achieved in the tunnel length from surface emissions alone. In this case, it may be necessary to feed additional saltation-size soil into the tunnel, measure the discharge, and also monitor gains and losses in the weight of a tray embedded in the surface near the downwind end of the tunnel to determine when surface transport capacity occurs.

## Emission Rate Coefficient

The net rate of entrainment of loose, erodible soil into the airstream is controlled by the emission rate coefficient ($C_{en}$ with units l/L). It also partially determines how quickly the saltation/creep transport approaches the surface transport capacity. To investigate $C_{en}$ in the wind tunnel, one can use a simple system consisting of loose saltation and creep-size sand and immobile elements that do not abrade. In this case, the mass conservation equation for the saltation/creep discharge becomes

$$\frac{dQ}{dx} = C_{en}\,(Q_{cp} - Q) \tag{4}$$

where x is distance along the wind direction, $Q_{cp}$ is saltation/creep discharge transport capacity, and Q is saltation/creep discharge.

For a tunnel working section of length, L, the solution to eq. 4 becomes

$$C_{en} = -\left(\frac{1}{L}\right) Ln\left(1 - \frac{Q}{Q_{cp}}\right) \tag{5}$$

meters also have been developed to enable convenient measurement of this energy for indirect determination of $C_{an}$ (Boyd, Skidmore, and Thompson, 1983; Hagen, Schroeder, and Skidmore, 1995).

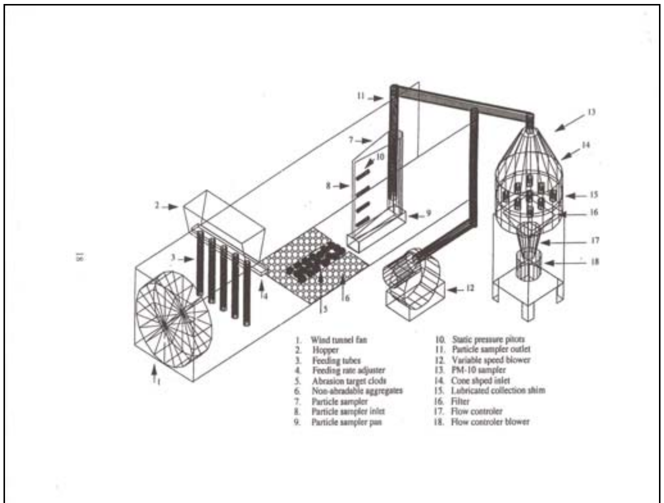


**Figure 2. Diagram of wind tunnel and sampling equipment used for clod abrasion tests.**

## Abrasion Rate Coefficient

Another fundamental property that governs field-scale erosion is the abrasion rate coefficient ($C_{an}$ with units 1/L ), which denotes the susceptibility to abrasion of immobile clods and crust. One method to determine $C_{an}$ in the wind tunnel is to feed known quantities of saltation-size sand across a target tray of clods or crust. A wind tunnel configuration used to measure $C_{an}$ is illustrated in Fig. 2 (Mirzamostafa et al., 1998) A mass conservation equation for the saltation/creep discharge over the target area is

$$\frac{dQ}{dx} = (1 - SFss_{an})\, F_{an}\, C_{an}\, Q \qquad (6)$$

where Q is saltation/creep discharge, $SFss_{an}$ is soil fraction of suspension-size from abrasion, $F_{an}$ is fraction of abrader impacting the target, and x is distance along the wind direction.

A solution for the preceding equation with target length, L, is

$$C_{an} = \left[\frac{1}{(1 - SFss_{an})\, F_{an}\, L}\right] Ln\left(\frac{Q_{out}}{Q_{input}}\right) \qquad (7)$$

The value of $F_{an}$ is one for solid crust cover and also for a surface that is 50 percent or more covered with clods. The target tray can be weighed after each test to determine total abrasion from the clods or crust. The saltation/creep component of soil from abrasion can be determined using a slot sampler. If the slot sampler is isokinetic and connected to particle sizing instruments (Fig. 2), components from abrasion, such as particulate matter less than 2. 5 and 10 microns in diameter also can be determined.

To facilitate testing of field samples without using a wind tunnel, the wind tunnel measurements of $C_{an}$ have been related to the logarithm of the crushing energy of clods and crust (Hagen, Skidmore, and Saleh, 1992). Crushing-energy meters also have been developed to enable convenient measurement of this energy for indirect determination of $C_{an}$ (Boyd, Skidmore, and Thompson, 1983; Hagen, Schroeder, and Skidmore, 1995).

## Breakage Rate Coefficient

As saltation/creep aggregates move downwind, a portion of the moving material breaks into suspension-size aggregates and no longer abrades the surface. The susceptibility to breakage of the moving saltation/creep is denoted as a breakage coefficient ($C_{bk}$ with units 1/L). This moving soil is significantly more resistant to breakdown from impact than the immobile clods and crust. Wind tunnel tests on some typical soils showed that the value of $C_{bk}$ is roughly 10 percent of the abrasion coefficient for clods from the same soil (Mirzamostafa et al., 1998).

To determine $C_{bk}$ in wind tunnel tests, saltation/creep-size soil aggregates can be cycled through a tunnel abrader feeder and across a noneroding tunnel floor multiple times to observe their rate of breakdown to suspension size. Recycling the soil can be accomplished by adding a bin beyond the tunnel exit to trap all the saltation and creep from each tunnel run. A mass conservation equation for this test condition is

$$\frac{dQ}{dx} = -C_{bk}\,(Q - Q_s) \qquad (8)$$

where Q is saltation/creep discharge, $Q_s$ is discharge of sand > 0.1 mm diameter, and x is distance along wind direction.

For practical purposes, $Q_s$ can be estimated as

$$Q_s = (SF_{san})\, Q \qquad (9)$$

where $SF_{san}$ is primary sand fraction > 0.1 mm diameter in the soil sample.

A solution of eq. 8 for the breakage rate coefficient at downwind length, L, is

$$c_{bk} = -\frac{1}{L\,(1 - SF_{san})} Ln\left(\frac{Q_{out}}{Q_{input}}\right) \qquad (10)$$

# SUMMARY AND CONCLUSIONS

Many aspects of wind erosion can be studied in wind tunnels. Attention to details through proper selection of nondimensional scaling parameters and instrumentation can improve the applicability of the tunnel results to the field scale. Soil loss ratios measured in wind tunnels frequently have been used for empirical erosion models. However, they generally require correlation to field measurements of wind erosion before they can be used. Through the efforts of many researchers, most of the critical, physical parameters that control wind erodibility of agricultural fields now have been identified. This report illustrates methodology than can be used to measure several of these critical parameters directly in a laboratory wind tunnel by using various surfaces, instruments, and tunnel configurations. This approach should lead to development of wind erosion models that are universally applicable in a wide range of conditions.

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