A new model for dust emission by saltation bombardment

Hua Lu, Yaping Shao
School of Mathematics, University of New South Wales, Sydney, Australia

Abstract. In this paper, we present an analysis on the mechanism of dust emission and describe a new model for the prediction of dust emission rate caused by saltation bombardment, based on the volume removal by impacting sand grains as they plough into the soil surface. The model predicts a relationship between the removed volume V and the particle impacting velocity U of the form V \propto U^n, with n = 2 \sim 3. The dust emission rate is found to be proportional to U^2, where \( U^* \) is friction velocity. These model predictions are consistent with wind tunnel and field observations. The model offers a new interpretation of observed data and a simple scheme for the calculation of dust emission.

1. Introduction

Dust produced by wind erosion is a major source of atmospheric aerosols that may have a considerable impact on atmospheric circulation patterns [Joussaume, 1990; Tegen and Fung, 1994]. For studies of atmospheric radiation and global circulation patterns, it is required to adequately estimate dust emission rate so that dust concentration in the atmosphere can be estimated. However, a satisfactory dust emission model so far does not exist, albeit the considerable effort of several research groups [e.g. Marticorena and Bergametti, 1995; Shao et al., 1996].

Dust emission rate has been conventionally expressed in terms of aerodynamic variables. For instance, field measurements have been carried out to establish a relationship between vertical dust flux \( F \) and surface friction velocity \( u^* \) [Gillette and Walker, 1977; Gillette, 1977; Nickling and Gillies, 1989, 1993]. Field data sets often have large scatter because wind erosion is influenced by a range of soil properties (e.g., soil texture, surface crust, soil compactness, and soil moisture), surface characteristics (e.g., roughness, vegetation cover, and topography), and atmospheric conditions (e.g., wind speed and precipitation). Consequently, it is often difficult to use the empirical relationships derived from field experiments to explain the physics involved in the erosion process. Although there is a general agreement that dust emission rate is proportional to \( u^* \) with \( n \) varying between 2 and 5, there is no clear understanding for what effects \( n \).

Wind tunnel experiments allowing control of soil texture and aerodynamic conditions have been carried out by Shao et al. [1993]. It has been found that saltation bombardment appears to be mainly responsible for dust emission. On the basis of wind tunnel observations, Shao et al. [1993, 1996] proposed that vertical dust flux is proportional to horizontal sand drift intensity. They also proposed a theory based on the concept of particle binding energy and energy balance of a single saltator during particle and surface collision. The theory of Shao et al. [1993] suggests that \( F \) is proportional to \( u^*_s \), in contrast to the \( u^* \) relationship suggested by Gillette and Passi [1988].

The model of Shao et al. [1993] has two intrinsic problems. First, it is difficult to accurately estimate the dust-particle binding energy \( \psi \) on either theoretical or experimental grounds. It can be shown that the uncertainty involved in the theoretical estimation of \( \psi \) is several orders of magnitude. Second, during particle/surface collision the kinetic energy of saltating particles is not conservative, as a proportion of the particle kinetic energy converted to heat. Alfaro et al. [1997] proposed a conceptually similar dust emission model as that of Shao et al. [1993]. However, the two models are significantly different from each other in a quantitative sense, precisely because of the different assumptions made to account for the proportion of the kinetic energy that is dissipated during particle-surface impact.

Using high-speed photography techniques, Rice et al. [1996a, b] carried out experiments to examine the possible mechanism of dust emission by saltation. Their observations revealed that sand grains saltating over a surface of loose fine particles excavate void-shaped craters in the bed. This phenomenon has been known since the earlier studies of Bagnold [1941, p. 57], who described an eroded surface as being "pitted with tiny bombardment craters a few grain diameters in size". Evidence
of craters were also found in several more recent experimental studies [Willets and Rice, 1985; Linsey, 1989; McEwan et al., 1992]. A similar phenomenon has been observed in metal erosion which occurs at larger particle impacting velocity. It has been found that an impacting particle may penetrate into the surface to a depth of a fraction of its own diameter, deforming the surface plastically to form a concavity having a radius of curvature similar to that of the particle. On the basis of the observations of crater formation, several models have been proposed for metal or ductile material removal by the impact of abrasive particles [Finnie and McFadden, 1978; Hutchings, 1977], which are generally in good agreement with experimental data. The starting point of these models is to consider the motion of impacting particles during particle/bed collision. The similarity between soil erosion and metal erosion motivates us to apply some of the analytical techniques used in the industry wear research to study dust emission during wind erosion.

This paper presents an analysis on the mechanism of dust emission and describes a new model for the prediction of dust emission rate caused by saltation bombardment. The model estimates dust emission rate on the basis of the volume removed by impacting sand grains as they plough into the soil surface. In section 2, a theoretical prediction for the volume removal, its relationship with particle impact velocity and impact angle, and that for dust emission rate are derived. A comparison of the theoretical predictions with wind tunnel and field data is given in section 3. Discussions on the role of soil erodibility and the possible measure of soil erodibility are given in section 4. Conclusions of the paper appear in section 5.

2. Dust Emission Model

In our dust emission model, we consider saltation bombardment as the main mechanism responsible for dust emission. The dust emission model consists of two components. The first component is to predict variables that characterize the saltation process, such as the number of saltating particles, particle impact velocity, and impact angle. The second component is to predict the amount of dust particles ejected by saltation bombardment. The saltation component of the model has been extensively studied by many researchers [Bagnold, 1941; Owen, 1964; Anderson and Haff, 1991] and therefore is not described in detail in this paper. The dust component of the model is described below.

2.1. Model Concept and Assumptions

The proposed model is based on the observation that sand grains saltating over a surface of loose fine particles excavate void-shaped craters in the bed. The model first calculates the crater volume and dust release created by individual saltating particles, and then estimates the dust emission due to a large number of saltating particles by a superposition of individual impacting events.

A similar approach used by Finnie and McFadden [1978] for ductile metal erosion is adopted here. The ploughing process of a single particle is illustrated in Figure 1. The impact particle is assumed to be angular with an equivalent diameter \( d \), a mass \( m = \frac{4}{3} \pi \rho_p d^3 \) (where \( \rho_p \) is particle density), and a moment of inertia \( I = \frac{2}{15} \pi d^5 \). The origin of the coordinate system is located at the centre of gravity of the impacting particle when the particle starts to contact the surface. It is assumed that the particle does not break during impact. It impinges upon the soil surface at a velocity \( U \) (immediately before impact) and an angle of attack \( \alpha \). The particle then ploughs into the surface and pushes soil particles ahead of it. The target soil flows plastically during the ploughing without fracture. The protruding tip of the incident particle ploughs a trajectory \((X_T, Y_T)\) into the target soil and forms a crater. The total volume of the grains ejected from the crater into the air is assumed to be equal to that of the crater. The volume of the crater can be estimated by solving the equation of particle motion and by determining the path of the particle as it moves through the soil (see Figure 1).

To derive the equations of motion for the ploughing saltator, the forces exerted by the target soil upon the saltator during the ploughing process need to be determined. For an analytical model, this can only be done under several simplifications that make the analysis mathematically tractable. These simplifications are listed below.

1. On average, impact particles have no initial rotation and small rotation during the ploughing process. It follows that for polyhedral particles, \( X_T \approx X + \frac{2}{3} \phi \) and \( Y_T \approx Y \), with \( \phi \) being the rotation angle, as shown in Figure 1.

2. The ratio of the vertical force to the horizontal force on the particle during ploughing is a constant \( K \). A reasonable value for abrasive grains is \( K = 2 \) [Finnie and McFadden, 1978].

![Figure 1](image.png)
3. A constant plastic flow pressure exists during ploughing, and its horizontal component is \( p \).

4. The depth over which surface contacts the particle is the same as that of the crater \( Y_T \), as illustrated in Figure 1.

5. The removed volume is the product of the area swept out by the particle tip and the width \( b \) of the ploughing face,

\[
V = b \int Y_T dX_T = b \int_0^{t_c} Y_T \frac{dX_T}{dt} dt
\]

where \( t_c \) is the time at which ploughing ceases.

6. The vertical and horizontal forces on the particle are located at the centre of the surface soil material in contact with the particle. The symmetrical picture of two-dimensional ploughing shown in Figure 1 can be understood as the average situation for grains that are tilted in either direction as they strike the surface. To be consistent with assumption 2, the projected contact area in the horizontal plane is twice that in the vertical plane.

Assumption 2 is sufficiently accurate if the particle rotation during the ploughing is small, and hence a geometrical similar configuration is maintained throughout the process. Although there is no direct observational evidence of the geometry, it is plausible to assume that \( K \) is a constant as the particle/bed contact time is small (< 10^{-2} s, [Rice et al., 1996a]). Experiments on force measurements of dry surface grinding [Marshall and Shaw, 1952] show an overall value of \( K \) close to 2 for angular abrasive grains. It seems reasonable to use this value in our analysis because the processes involved in ploughing and grinding are similar. The magnitude of \( K \) may vary with the shape of the impact particle, and it is possible that \( K \) increases as the particles become less angular and more spherical. Experiments of Marshall and Shaw [1952] on dry surface grinding also shows that the value of \( K \) is usually larger than 1 and less than 5. This suggests that the uncertainty brought by \( K \) may be limited. As it will become clear later, the precise value of \( K \) does not significantly influence the conclusions of our study.

### 2.2. Equations of Motion for Ploughing Particles

The equations of particle motion in the \( X \) and \( Y \) directions and the equation of angular rotation are

\[
m \frac{d^2X}{dt^2} + pYb = 0 \quad \text{(1)}
\]

\[
m \frac{d^2Y}{dt^2} + KpYb = 0 \quad \text{(2)}
\]

\[
\frac{d^2\phi}{dt^2} + \frac{pbY(d/2 - Y) - 2(KpYb)Y}{\beta} = 0 \quad \text{(3)}
\]

where \( pYb \) and \( KpYb \) are the horizontal and vertical components of the resistance force acting upon the ploughing particle. It is assumed that \( Y_T = Y \) and \( X_T = X + \frac{d}{2} \phi \).

Equations (1) and (2) can be solved with the initial conditions \( (X|_{t=0}, Y|_{t=0}) = (0, 0) \) and \( \left( \frac{dX}{dt} \bigg|_{t=0}, \frac{dY}{dt} \bigg|_{t=0} \right) = (U \cos \alpha, U \sin \alpha) \):

\[
X(t) = \frac{U \sin \alpha}{\beta K} \sin \beta t + \left( U \cos \alpha - \frac{U \sin \alpha}{K} \right) t \quad \text{(4)}
\]

\[
Y(t) = \frac{U}{\beta} \sin \alpha \sin \beta t \quad \text{(5)}
\]

where \( \beta = \sqrt{\frac{2Kb}{m}} \).

With the initial conditions \( \phi|_{t=0} = 0 \) and \( d\phi/dt|_{t=0} = 0 \), the solution for angular rotation \( \phi \) is

\[
\phi(t) = \frac{3.75U^2 \sin^2 \alpha}{\beta^2 d^2} \left[ 2(\beta t)^2 + \cos 2\beta t - 1 \right] + \frac{3U \sin \alpha}{d} (\sin \beta t - \beta t) \quad \text{(6)}
\]

### 2.3. Volume Removal

It follows from assumption 5 and equations (4), (5), and (6) that the volume removed by a single impact can be calculated using the following expression:

\[
\frac{V}{b} = \frac{U^2 \sin^2 \alpha}{\beta^2} \left[ (2 - \cot \alpha) \cos \beta t_c + \cot \alpha - 1.5 - 0.5 \cos 2\beta t_c \right] + \frac{U \sin \alpha}{\beta} \left[ \frac{3.75U^2 \sin^2 \alpha}{\beta d} \left( -\frac{1}{2} \sin \beta t_c + \frac{1}{6} \sin 3\beta t_c \right) + \frac{7.5U^2 \sin^2 \alpha}{d} \left( \frac{1}{\beta^2} \sin \beta t_c - \frac{1}{\beta} t_c \cos \beta t_c \right) \right] \quad \text{(7)}
\]

where \( t_c \) is the impact duration.

Two ploughing cases should be distinguished. In case 1, the impact particle ploughes into the target soil and, subsequently, leaves it when \( Y_T \) becomes zero. In case 2, the particle stops during its scooping action at some depth as its kinetic energy is exhausted, that is, \( \frac{dX}{dt}|_{t=t_c} = 0 \). For case 1, we have \( Y(t_c) = Y_c = 0 \), \( \sin \beta t_c = 0 \), and \( t_c = \pi/\beta \), as can be seen from equation (5). It follows that equation (7) can be simplified to

\[
\frac{V}{b} = \frac{U^2 (\sin 2\alpha - 4 \sin^2 \alpha)}{\beta^2} + \frac{7.5\pi U^3 \sin^3 \alpha}{\beta^3 d} \quad \text{(8)}
\]

For case 2, the initial condition \( \frac{dX}{dt} = \frac{dX}{dt} + \frac{d\phi}{dt} = 0 \) leads to a rather complex expression of \( t_c \), which can be derived from equations (4) and (6)

\[
U \cos \alpha - 2U \sin \alpha - \frac{3.75U^2 \sin^2 \alpha}{\beta d} \sin(2\beta t_c) + 2U \sin \alpha \cos \beta t_c + \frac{7.5\pi U^2 \sin^2 \alpha}{\beta^2 d} \beta t_c = 0 \quad \text{(9)}
\]
The impact duration $t_c$ can be determined numerically from the above equation for a given $\alpha$ and then used in equation (7) to calculate the volume removal.

We now examine the relationship between the volume removal and the particle impact velocity on the basis of equation (8). We note that the maximum depth of the crater is

$$Y_{\text{max}} = \frac{U}{\beta} \sin \alpha$$

(10)

and the ratio of $Y_{\text{max}}$ to the particle radius $d/2$ is

$$\lambda = \frac{2U \sin \alpha}{d \beta} = \frac{2U \sin \alpha}{\sqrt{\frac{\pi \rho_p}{6pK} \sqrt{d/b}}}$$

Both $Y_{\text{max}}$ and $\lambda$ are functions of particle impact velocity and angle; $\lambda$ is independent of particle diameter $d$ if $b = d$ is assumed. In terms of $\lambda$, equation (8) can be rewritten as

$$\mathbf{V} = \frac{mU^2 \beta^2}{2p} (\sin 2\alpha - 4 \sin^2 \alpha) + 0.94 \pi d^2 b \lambda^3$$

(11)

where we assumed $K = 2$.

By fixing the properties ($U$, $\alpha$, $d$, and $\rho_p$) of impact saltator, the effects of soil surface hardness on the volume removal and the relation between $\mathbf{V}$ and $U$ can be shown by equation (11). The larger horizontal plastic flow pressure $p$ (harder surface), the smaller $\mathbf{V}$ (less erosion by saltation bombardment) is obtained. A precise analysis of the effect $p$ on the relationship between $\mathbf{V}$ and $U$ can be done by considering the ratio of the volume removals by the same impacting particle with two different velocities $U_{\text{ref}}$ and $U$

$$\frac{\mathbf{V}(U)}{\mathbf{V}(U_{\text{ref}})} = \left( \frac{U}{U_{\text{ref}}} \right)^n \frac{\sin 2\alpha - 4 \sin^2 \alpha + 7.5 \pi U \sin^3 \alpha / \beta d}{\sin 2\alpha - 4 \sin^2 \alpha + 7.5 \pi U_{\text{ref}} \sin^3 \alpha / \beta d}$$

(12)

where $U_{\text{ref}}$ is an arbitrary reference velocity that can be set, for instance, as the average particle impact velocity during a wind erosion event. If the volume removal is proportional to the $n$th power of $U$, we obtain

$$\left( \frac{U}{U_{\text{ref}}} \right)^{-n} = \frac{\sin 2\alpha - 4 \sin^2 \alpha + 7.5 \pi (U/U_{\text{ref}}) \lambda_{\text{ref}} \sin^2 \alpha}{\sin 2\alpha - 4 \sin^2 \alpha + 7.5 \pi \lambda_{\text{ref}} \sin^2 \alpha}$$

(13)

where $\lambda_{\text{ref}}$ is the crater depth to particle radius ratio corresponding to $U_{\text{ref}}$.

From equation (12), exponent $n$ can be calculated for an arbitrary given value of $\alpha$, $\lambda_{\text{ref}}$, and $U_{\text{ref}}$. It is widely accepted that $\alpha$ is typically between 10° and 15° [e.g. Anderson and Haff, 1991; Rice et al., 1995]. The wind tunnel study of Rice et al. [1995] shows that $U$ falls mostly between 3 and 4 m/s for saltator diameter $d = 150 \sim 600 \mu m$ and friction wind velocity $u_* = 0.4 \text{ m/s}$. By setting $U_{\text{ref}} = 3 \text{ m/s}$, $K = 2$, $b = d$, and $\rho_p = 2650 \text{ kg/m}^3$, Table 1 summarizes the values of $\lambda_{\text{ref}}$, $\lambda$ (corresponding to $U$), and $n$ estimated for different of $p$, $\alpha$, and $U/U_{\text{ref}}$. It reveals the following important facts:

1. For fixed impact saltator conditions (given $\alpha$ and $U/U_{\text{ref}}$), $n$ increases from 2 to 3 with decreasing $p$. This implies that $\mathbf{V}$ tends to be proportional to $U^3$ for soft, loose soils (corresponding to small $p$ and hence large $\lambda$), while it tends to be proportional to $U^2$ for more compact soils (corresponding to large $p$ and hence small $\lambda$).

2. For given $p$, $n$ is rather insensitive to $U/U_{\text{ref}}$ for fixed $\alpha$. This implies that a plot of $\mathbf{V}$ against $U$ on a log-log scale is essentially a straight line for given soil surface conditions.

3. For given $p$, $n$ increases with $\alpha$ for fixed $U/U_{\text{ref}}$.

4. Equation (12) shows that the saltating particle size $d$ has no explicit influence on the value of $n$ and $\lambda$ for given $U$ and $\alpha$ (as $b = d$ is assumed). However, both $U$ and $\alpha$ vary with $d$ because of the particle/air interaction on the saltator trajectories. Rice et al. [1995] showed that $U$ decreases and $\alpha$ increases with increasing $d$. Since $n$ is more sensitive to the change of $\alpha$ than to the change of $U$, the overall effect of $d$ on $n$ is likely that $n$ increases with $d$.

For case 2, in which the particle is trapped in the soil and does not rebound, equation (9) can be simplified to

$$2 \cos \beta t_c - 2 + \cot \alpha + \frac{7.5 U \beta_c \sin \alpha}{\beta d} - \frac{3.75 U \sin \alpha}{\beta d} \sin 2 \beta t_c = 0$$

(14)

or in terms of $\lambda$

$$2 \cos \beta t_c - 2 + \cot \alpha + 3.75 \lambda_\beta \beta t_c - 1.875 \lambda \sin 2 \beta t_c = 0$$

(15)

For $\lambda \rightarrow 0$, equation (15) has no solution for $t_c$ for $\alpha \leq \tan^{-1}(1/4)$. It is therefore unlikely for particles with an impacting angle between 0° and 14° to be trapped in soil. Under this circumstance, particles must leave the surface while still in the ploughing motion. The experimental results of Rice et al. [1996a] support this conclusion and their high-speed photography showed that saltating sand grains with an impact angle between 10° and 15° usually rebound after excavating a crater on the soil surface. However, solution exists for $t_c$ for larger impacting angles, which implies that particles may be trapped in soil in those circumstances. For instance, for $\alpha = 30°$ and $\lambda = 0.1$, the solution of $\beta t_c$ from equation (15) is $\beta t_c = 1.829$. It follows from equation (7) that $n = 3$. A large impact angle does happen over an irregularly shaped soil surface. As observed in the wind tunnel study by Alfaro et al. [1997], a considerable proportion of sand grains saltating over a loosely packed clay particle surface do not rebound.
There exists a critical angle $\alpha_c$ that separates the two ploughing cases and $\alpha_c$ is positively related to $\lambda$. For instance, for $\lambda = 0.1$, $\alpha_c$ is about 20° compared with about 14° for $\lambda \to 0$.

### 2.4. Vertical Dust Flux

We first consider dust emission from a soil that contains multisized dust particles and uniform sand particles (with diameter $d$). If $n_s$ is the particle number flux density (number of impacting particles per unit area per unit time) and $f$ is the fraction of dust contained in $V$, the vertical dust flux caused by saltation bombardment can be calculated by

$$F(d) = c_N n_s \rho_b f V$$

(16)

where $\rho_b$ is the bulk density of soil and $c_N$ is a constant of proportionality less than 1, as a proportion of dust particles may stick on aggregates contained in $V$.

Following the well-developed line of sand saltation momentum transfer near the surface, we have

$$n_s = \frac{\rho u_s^2 (1 - u_{st}^2 / u_s^2)}{m(U_1 \cos \alpha_1 - U \cos \alpha)}$$

(17)

where $u_{st}$ is the threshold friction velocity for sand particles, $U_1$ is the ejection velocity of sand particles, and $\alpha_1$ is the ejection angle [Raupach, 1991].

Substituting (17) and (8) into (16), we obtain

$$F(d) = c_N f \rho_b U^2 \rho u_s^2 (1 - u_{st}^2 / u_s^2)$$

$$\frac{U_1 \cos \alpha_1 - U \cos \alpha}{\beta d}$$

(18)

According to Owen [1964], the horizontal saltation flux for a dry soil with uniform particles is

$$Q(d) = \frac{c_p u_s^3}{g} (1 - u_{st}^2 / u_s^2)$$

(19)
where \( c \) is the Owen coefficient and \( g \) is gravitational acceleration. Equation (18) can be expressed in terms of \( Q(d) \) as

\[
F(d) = \frac{C_{gf} p_b}{2p} Q(d) \\
\left( \sin 2\alpha - 4 \sin^2 \alpha + C_{\beta u_*} \sqrt{\frac{p_r}{p}} \right)
\]

(20)

where

\[
C_{\alpha} = c_N \left( \frac{U}{U_1 \cos \alpha_1 - U \cos \alpha} \right) \left( \frac{U}{u_*} \right)
\]

\[
C_{\beta} = \left( 7.5 \pi \sin^3 \alpha \sqrt{\frac{\pi d}{6Kb}} \right) \left( \frac{U}{u_*} \right).
\]

As \( U/(U_1 \cos \alpha_1 - U \cos \alpha) \) is of the order of 1, \( U/u_* \) is of the order of 10 [Shao et al., 1993] and the Owen coefficient is typically 0.8 to 1 [Shao et al., 1996]; \( C_{\alpha} \) is approximately \( 10CN \). By assuming \( \alpha = 13^\circ \) and \( b = d \), \( C_{\beta} \) is approximately 0.137 \( \frac{U}{u_*} \), which is of the order of 1. Equation (20) then can be simplified to

\[
F(d) = \frac{C_{gf} p_b}{2p} \left( 0.24 + C_{\beta u_*} \sqrt{\frac{p_r}{p}} \right) Q(d)
\]

(21)

To estimate dust emission rate from a soil with a particle size distribution \( p(d) \), we separate soil particles into the categories of dust and sand. An integration of equation (21) over sand particle sizes gives the total dust emission rate \( F \) induced by saltation bombardment of sand grains of all sizes

\[
F = \int_{d_1}^{d_2} F(d)p(d) \delta d
\]

(22)

where \( d_1 \) and \( d_2 \) are the lower and upper bound of sand particle diameters. The ratio between the total vertical dust flux and the total horizontal sand flux is

\[
\frac{F}{Q} = \frac{\int_{d_1}^{d_2} F(d)p(d) \delta d}{\int_{d_1}^{d_2} Q(d)p(d) \delta d}
\]

(23)

As an approximation, it is possible to simplify the above equation as

\[
\frac{F}{Q} = \frac{C_{gf} p_b}{2p} \left( 0.24 + C_{\beta u_*} \sqrt{\frac{p_r}{p}} \right)
\]

which is a simple rearrangement of (21).

Equation (24) reveals several qualitatively important relationships: (1) since \( Q \) is proportional to \( u_*^i \), \( F \) must be proportional to \( u_*^i \) with \( i = 3 \sim 4 \); (2) the saltation bombardment efficiency ratio \( F/Q \) is linearly proportional to the fraction of dusts contained in the parent soil \( f \) and inversely proportional to soil surface hardness parameter \( p^K \) with \( k_1 = 1 \sim 1.5 \). For large \( p \) (hard surface), \( k_1 \approx 1 \), and for smaller \( p \) (soft surface), \( k_1 \approx 1.5 \); (3) for sufficiently large \( p \) so that \( C_{\beta u_*} \sqrt{\frac{p_r}{p}} \ll 0.24 \), \( F/Q \) would be independent of \( u_* \), while for sufficiently small \( p \) so that \( C_{\beta u_*} \sqrt{\frac{p_r}{p}} \gg 0.24 \), \( F/Q \) increases linearly with \( u_* \).

The value of \( C_N \), the fraction of dust particles that become suspended from the ejected soil volume, is not amenable to direct measurement. However, the experiments of Rice et al. [1996a] show the grains from the crater are ejected into the air as a dense cloud and gradually disperses. Dust emissions in natural conditions are usually observed as soon as saltation is initiated [Gillette and Walker, 1977]. It suggests that \( C_N \) should not be much smaller (several orders smaller) than 1 for loosely picked particle surfaces that are prone to wind erosion. More detailed experimental studies are needed to fully describe this parameter. In reality, particle impact velocity \( U \) and angle \( \alpha \) are also functions of particle size \( d \) [Rice et al., 1995, 1996b]. If we substitute equation (20) into equation (23), the behavior of \( F/Q \) is much more complex. The analysis presented in this section can be used to explain some of the large scatter encountered in field data.

Using equation (22) to calculate the total vertical dust flux \( F \), two types of information about soil texture are required. One is a minimally dispersed particle size distribution (MDPSD) which reflects the in-situ particle size distribution \( p(d) \) in equations (22) and (23)). Another is the finite content \( f \), required in equations (21) and (24), which cannot be well represented by MDPSD but can be estimated using the fully dispersed method. Both the minimally dispersed particle size distribution (MDPSD) and the fully dispersed particle size distribution (FDPSD) are analyzed by Griffith University Particle-Sizing Laboratory. They are expressed as 38 size classes from 2 to 1159 \( \mu m \). The techniques used to obtain these particle size distributions are described by McTainsh et al. [1997]. The lower and upper limits for sand particle diameters \( d_1 \) and \( d_2 \) can be set as 60 \( \mu m \) and 1159 \( \mu m \) for simplicity [Bagnold, 1941] or can use more strict aerodynamic-based definitions, as suggested by Shao et al. [1996]. The upper limit for the dust particle size can be defined according to aerodynamic conditions [Shao et al., 1996], or defined as required for comparison with observations (for example, set to 20 \( \mu m \)). If high-resolution FDPSD is available, \( f \) can be estimated as the sum of each dust particle fractions, or as a single fraction if the information about dust emission rate from the specific particle size range is of interest.

3. Comparison with Experiments

3.1. Wind Tunnel Data

Rice et al. [1996a] carried out wind tunnel studies on crater volumes created by 250 \( \sim 300 \mu m \) impact-
ing particles over a smooth and fine-grained unaggregated soil surface. They analyzed seven craters and calculated the volume removal from measured contour profiles. For a fixed friction velocity \( u_\bullet = 0.4 \text{ m/s} \), they found the volume of the craters is in the range of \( 0.1 \sim 0.6 \text{ mm}^3 \) with the maximum crater depth being around 0.2 mm. The analysis presented in the previous section can be compared with their experimental data. To apply equations (8) or (11) to predict volume removal and the maximum crater depth, the horizontal component of plastic flow pressure \( p \) must be specified. One possibility is to estimate \( p \) by combining \( \beta = \sqrt{\frac{\rho E K_b}{m}} \) and \( \lambda = \frac{2U \sin \alpha}{bd} \), which gives \( p = \frac{4mU^2 \sin^2 \alpha}{K_b d_b} \). For saltators ranging between 250 and 300 \( \mu \text{m} \), Rice et al. [1996a] reported the mean value of impact energy \( \frac{1}{2} mU^2 = 2.31 \text{ g cm}^2/\text{s}^2 \) for crust 1 (a fragile covering of weakly bonded surface containing uniform particles as unaggregated soil [Rice et al., 1996a, Table II]. It gives \( U = 3.51 \text{ m/s} \) for \( d = 300 \mu \text{m} \) and \( U = 4 \text{ m/s} \) if \( d = 275 \mu \text{m} \). In addition, using the same wind tunnel and \( u_\bullet = 0.4 \text{ m/s} \), Rice et al. [1995] reported collision data for particles ranging between 150 ~ 250 \( \mu \text{m} \) and 300 ~ 355 \( \mu \text{m} \), respectively. For the 150 ~ 250 \( \mu \text{m} \) impactor, \( U = 3.80 \pm 0.65 \text{ m/s} \) (mean±SD). For the 300 ~ 355 \( \mu \text{m} \) impactor, \( U = 3.30 \pm 0.62 \text{ m/s} \). Therefore it can be concluded that the average impact velocity on unaggregated soil by 250 ~ 300 \( \mu \text{m} \) particles should be well around \( U = 3.5 \text{ m/s} \). Since \( Y_{\text{max}} = 0.2 \text{ mm} \) and maximum saltator diameter \( d = 300 \mu \text{m} \) [Rice et al., 1996a], we have \( \lambda = \frac{2Y_{\text{max}}}{d} = \frac{4}{3} \). Setting \( K = 2 \), \( b = d \), \( \alpha = 13^\circ \), \( U = 3.5 \text{ m/s} \), and \( \lambda = \frac{4}{3} \), we obtain \( p = 967.57 \text{ N/m}^2 \).

Table 2 shows the volume removal, \( V \), and the maximum crater depth, \( Y_{\text{max}} \), both estimated using equations (8) and (10) with \( p = 967.57 \text{ N/m}^2 \). Three different values of \( U \), \( \alpha \), and \( d \) within the experimental data range are used to account for the uncertainties.

The predicted volume removal and crater depth shown in Table 2 are in good agreement with the data reported by Rice et al. [1996a]. It is shown that for given impact velocities and impact angles, both volume removal and crater depth increase with saltating particle size. This is consistent with the wind tunnel observations of Shao et al. [1993]. Table 2 also shows that both the volume removal and the crater depth increase with impact velocity and impact angle for a given impact particle size. It is coherent with the measurement of Rice et al. [1996b]. With a cohesionless bed of sand-sized particles, Rice et al. [1996b] found that the number of ejected grains per collision increased with increasing impact angle up to approximately 15\(^\circ\). Above this angle the number of ejected grains appeared to decrease. It is predicted that the smallest crater volume is 0.054 \( \mu \text{m}^3 \), and the largest crater volume is 0.5 \( \mu \text{m}^3 \). Both values are slightly smaller than 0.1 \( \mu \text{m}^3 \) and 0.6 \( \mu \text{m}^3 \), measured by Rice et al. [1996a]. The small underestimation may be resulted by the overestimation of \( p \). It could also be due to the fact that the crater may have a nonsmooth boundary which makes the actual volume of the crater slightly larger than the model defined. It is caused by the microheterogeneous nature of soil surface, in which the particles are removed in their entirety.

The present model can also be compared with the investigations of aeolian abrasion of rocks and minerals. Dietrich [1977] concluded that the fundamental parameters that control aeolian abrasion are the kinetic energy of the impacting grain and the bond strength of the abraded material. This was confirmed by Greely and Iversen [1985] who investigated the susceptibility of surfaces to abrasion, \( S_a \), defined as mass of material eroded per particle impact. They found that for a given impact particle size, \( S_a \) is proportional to \( U^2 \), while for a given impact velocity, \( S_a \) is proportional to \( d^3 \). Therefore

\[
S_a \propto d^3 U^2 \propto \frac{mU^2}{2}
\]

Since \( S_a = \rho_p V \), these observations are fully consistent with equation (11) for large \( p \) with the first term dominant over the second term, which is precise enough for shallow abrasion.

### 3.2. Field Data

For practical purposes, it is useful to establish a simple relationship between dust emission rate and wind speed for given soil conditions. Gillette [1977] presented field measurements of vertical dust flux \( F \) and horizontal sand flux \( Q \) as a function of friction velocity \( u_\bullet \) for nine different soils. It was shown that while the \( Q \propto u_\bullet^2 \) relationship describes well their observed data, the \( F \) and \( u_\bullet \) relationship shows large scatter although \( F \)}
generally increases with $u_*$. Gillette and Passi [1988] suggested that dust emission rate is probably proportional to $u_*^4$,

$$ F = \alpha_g u_*^4 (1 - u_{st}/u_*) \quad u_* \geq u_{st} \quad (25) $$

where $u_{st}$ is the saltation threshold velocity and $\alpha_g$ is a dimensional coefficient.

Nickling and Gillies [1989] reported vertical dust emission rate at 13 sites in southern Arizona. A considerable degree of scatter exists in the data if no distinction is made between the soil surface features. They partitioned the data on the basis of surface morphology and land use, and on the basis of the percentage of silt and clay measured, respectively. The regressive relationship between vertical flux $F$ and wind friction velocity $u_*$ obtained from their data is $F \propto u_*^i$, in which $i$ confined within $i = 3 \sim 4$. Similar results are obtained in the dust emission experiment over Mali, West Africa [Nickling and Gillies, 1993] for five different soil surface conditions. These $F \propto u_*^i$ relationships are well predicted by the dust emission model derived in this paper.

We now examine the performance of our model against the field measurements of Gillette [1977], using equations (22) and (21). Because very limited data points are available for soils 7 and 8, only soils 1, 2, 3, 4, 5, 6, and 9 are used for comparison. According to Gillette [1977], soils 1, 2, 4, and 5 have sand texture, soil 3 has a loamy sand texture, soil 6 has a sandy loam texture, and soil 9 has a clay texture.

Since vertical dust flux $F$ is proportional to horizontal sand drift flux $Q$, two kinds of comparisons are attempted for $F$. One is fully simulated and the other is semisimulated. The fully simulated $F$ is obtained by first calculating $Q$, using the saltation model of Shao et al. [1996], and then relating $F$ to the predicted $Q$ by using equation (22). In order to use equation (24) to predict $F$, the value of $p$ must be determined. The values of $p$, given in Table 3, are calculated posteriorly by fitting measured $F$, using equation (24), and measured $Q$. The fitted values of $F$ are called semisimulated $F$. The discussion on the correctness of these fitted values of $p$ and their comparison with the measurements are given in section 4.

One of the most important parameters for simulating $Q$ is the threshold friction velocity $u_{st}$. The comparison between model and observation can only make sense when the simulated $u_{st}$ is comparable with the measured ones. In this study, the calculation of $u_{st}$ follows Shao et al. [1996]. It is based on the formula of Greeley and Iversen [1985] for bare, dry soils and takes the influences of soil moisture, vegetative residue, and surface roughness into account. According to Gillette [1977] and Gillette [1988], both soil moisture contents and vegetative residue were very low and had little effects on total soil movement for soils 1 to 5. Our simulation showed that $u_{st}$ (hence $Q$) is not very sensitive to the fraction of nonerodible elements (see Table 4) for small values of vegetative residue but is sensitive to soil moisture. Therefore the simulations of $u_{st}$ (hence $Q$) for soils 1, 3, 4, and 5 were done by varying soil moisture within the measured range, until the simulated $u_{st}$ is close to the measured ones. For soils 2, 6, and 9 the measured soil moisture was given by Gillette [1977]. These measurements were used in our simulation without adjustment. As the particle size distributions for the seven soils have a certain amount of particles with a diameter $d = 70 \sim 80 \mu m$, the estimated $u_{st}$ given in Table 4, is the threshold friction velocities for $d = 75 \mu m$. The measured $u_{st}$ are as reported by Gillette [1977], except for soil 6. In the work of Gillette [1988], $u_{st}$ for soil 6 is given as 0.6 m/s. However, in Figure 4 of Gillette [1977], the smallest value of $Q$ for soil 6 is shown as $u_{st} \approx 0.52$ m/s. Both data are listed in Table 4.

The (dry sieved) particle size distributions of soil 3 and soil 4, given by Gillette and Walker [1977], were used to calculate $Q$ (Figure 2). Since soils 1, 2, and 5 are sandy soils and have similar features in soil aggregates, soil moisture and surface roughness, as well as horizontal sand fluxes, their (dry sieved) particle size distribution should not differ greatly from that of soil 4. Therefore we assumed that soils 1, 2, 4, and 5 have the same (dry sieved) particle size distribution but different dust particle contents, which were given by Gillette [1977] (see Table 3). To test the effect of particle size distribution, we replaced the particle size distribution (PSD) of soil 1, 2, 4, and 5 with a high-resolution MDPSD of an Australian sandy soil described by Leya et al. [1993]. Similarly, we replaced the PSD of soil 3, 6, and 9 with a high-resolution MDPSD of an Australian loamy sand, loam (cracking sesquioxide), and clay (black earth), respectively. The particle size distributions of the Aus-

<table>
<thead>
<tr>
<th>Soil 1</th>
<th>Soil 2</th>
<th>Soil 3</th>
<th>Soil 4</th>
<th>Soil 5</th>
<th>Soil 6</th>
<th>Soil 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_o$</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$p_o$ (kg/m$^3$)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>800</td>
</tr>
<tr>
<td>Fine particle contents $f$ (%)</td>
<td>4</td>
<td>4.5</td>
<td>18.5</td>
<td>3.2</td>
<td>6.9</td>
<td>22.3</td>
</tr>
<tr>
<td>Horizontal pressure $p$ (10$^5$ N/m$^2$)</td>
<td>20</td>
<td>20</td>
<td>0.5</td>
<td>25</td>
<td>25</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>350</td>
</tr>
</tbody>
</table>
Australian soils are shown together with those of Gillette and Walker [1977] in Figure 2.

In all tests we used \( C_p = 1.37 \), \( c = 0.8 \) and \( \rho_p = 2650 \text{ kg/m}^3 \). Because the semisimulated \( p \) values (see Table 3) are all about \( 10^2 \sim 10^3 \) times larger than \( \rho_p \), the second term in equation (24) is negligible even if \( C_p \) is set to as large as 10. While the fine particle contents given by Gillette [1977] are for \( d < 50 \mu m \), the emitted dust particles were measured for \( d < 20 \mu m \) and thus the value of \( f \) in equation (24) should be set to represent the dust fraction for \( d < 20 \mu m \). However, the highly erodible sandy soils are often bimodal with one mode close to 2 \( \mu m \) and the other close to 180\( \mu m \). The fraction of particles with diameter between 20 and 50 \( \mu m \) was negligible. For this reason, the values of \( f \) used in our tests were the fraction for \( d < 50 \mu m \) given by Gillette [1977]. The bulk density of fine-textured surface soils is in the range of 1000 to 1300 kg/m\(^3\) and coarse-textured surface soils are usually in the range of 1300 to 1800 kg/m\(^3\) [Foth and Turk, 1972]. The bulk density of loamy soils, according to Gillette [1988], are in the range of 600 \sim 950 kg/m\(^3\). For soils 1 to 5, which are fine, loose sand or loamy sand and have only a small amount of aggregates larger than 0.84 mm, we assumed \( C_\alpha = 5 \) and \( \rho_b = 1000 \text{ kg/m}^3 \). The value \( C_\alpha = 5 \) implies that about 40\% of the dust particles contained in the removal crater will not be released if we assume \( U/u_\ast = 10 \) and \( c = 0.8 \). For soil 6, which is cloddy sandy loam with a dry aggregate mode around 100 mm and 36.7\% loose material, we assumed \( C_\alpha = 2 \).

### Table 4. Soil Parameters Used for Calculation of Sand Drift \( Q \) for Comparison with the Experimental Data of Gillette [1977]

<table>
<thead>
<tr>
<th>Soil 1</th>
<th>Soil 2</th>
<th>Soil 3</th>
<th>Soil 4</th>
<th>Soil 5</th>
<th>Soil 6</th>
<th>Soil 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil moisture (%)</td>
<td>0.8</td>
<td>0.99</td>
<td>1.0</td>
<td>0.5</td>
<td>0.65</td>
<td>0.75</td>
</tr>
<tr>
<td>Nonerodible elements (%)</td>
<td>0.45-0.8</td>
<td>0.01-0.1</td>
<td>0-0.05</td>
<td>1-1.5</td>
<td>0.8-1.3</td>
<td>0.05</td>
</tr>
<tr>
<td>Nonerodible elements Used</td>
<td>0.6</td>
<td>0.1</td>
<td>0.05</td>
<td>1.5</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>Observed ( u_\ast ) (m/s)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.52-0.6</td>
</tr>
<tr>
<td>Simulated ( u_\ast ) (m/s)</td>
<td>0.253-0.26</td>
<td>0.256-0.258</td>
<td>0.256-0.257</td>
<td>0.246-0.254</td>
<td>0.251-0.26</td>
<td>0.2453</td>
</tr>
<tr>
<td>Simulated ( u_\ast ) Used</td>
<td>0.2561</td>
<td>0.2576</td>
<td>0.2572</td>
<td>0.2542</td>
<td>0.2545</td>
<td>0.2430</td>
</tr>
</tbody>
</table>

**Figure 2.** Particle size distributions (PSD) for sand (soils 1, 2, 4 and 5), loamy sand (soil 3) comparison with those given by Gillette and Walker [1977] (in the same form given by Gillette and Walker [1977]). The dotted curve is the particle size distribution of Gillette and Walker [1977], and the solid curve is Australian soil PSD assigned. Assumed PSDs for sandy loam and clay used in the simulation are also shown.
Figure 3. Comparison of simulated using PSDs of Gillette and Walker [1977] (solid curve), simulated using assigned PSDs, and observed (solid circles) horizontal sand drift $Q$ (left-hand side) and that of fully simulated (solid curve: using predicted $Q$ by PSDs of Gillette and Walker [1977]; dotted, using predicted $Q$ by assigned PSDs), semisimulated (using observed $Q$, dashed curve plus solid circles) and observed (crosses) vertical dust flux $F$ (right-hand side) versus friction velocity $u_*$ for Gillette [1977] soils 1 to 5. Parameters used for the comparison are listed in Tables 4 and 3.
and \( \rho_b = 800 \text{ kg/m}^3 \). For the clay textured soil 9, which has only 9.3% loose particles, we assumed \( C_n = 1 \) and \( \rho_b = 700 \text{ kg/m}^3 \).

Figure 3 shows a comparison of simulated and observed horizontal sand fluxes, \( Q \), and a comparison of the fully simulated (using simulated \( Q \) to calculate \( F \)), semisimulated (using observed \( Q \) to calculate \( F \)) and observed vertical dust flux \( F \) for soils 1 to 5. Although some of the parameters used for the simulation could not be estimated accurately, the predicted \( Q \) and \( F \) and observed \( Q \) and \( F \) are in good agreement for all soils, except soil 2. In that case, the simulated \( Q \) is about 5 times larger than observed, while the semisimulated \( F \), is smaller than both measured and fully simulated. This indicates that soil 2 may have a different particle size distribution (the typical mode may not be close to 180 \( \mu \text{m} \)) although it was classified as a sandy soil. It is interesting to observe that the simulation of \( Q \) is, somehow, not very sensitive to the particle size distribution and its resolution, while it depends strongly on \( u_* \). It is surprising to see that the simulated \( Q \) and hence \( F \), using the assigned PSDs (of the Australian soils), are very close to those obtained using the PSDs given by Gillette and Walker [1977] (Figure 3). We have also repeated the simulation by using nine other PSDs for sand and loamy sand soils from the Australian Mallee area. The same observation can be made. For soil 6 and 9 the fully simulated dust fluxes do not agree well with the observations, because of the poor performance of the saltation model for aggregated soils (Figure 4). However, the semisimulated vertical dust fluxes for these two soils still agree well with the observed data.

Despite the advantages of parameterizing the dust emission rate as a function of wind speed, a universally valid expression of \( F \) in terms of \( u_* \), which accounts only for the aerodynamic effects, may not exist, as pointed out by Shao et al. [1996]. The wind tunnel experiment of Shao et al. [1993] showed that saltation bombardment is the main mechanism responsible for dust emission during wind erosion. It is therefore justified to relate vertical dust emission flux to horizontal sand drift intensity. It has been found in several experimental studies [Gillette, 1977; Nickling and Gillies, 1989; Shao et al., 1993] that the ratio \( F/Q \) does not depend systematically on \( u_* \). Because of the complexities involved in dust emission, it appears difficult to simply express \( F \) in terms of \( u_* \) with a fixed exponent and expect the relationship to be applicable for all soil types. While Gillette and Passi [1988] and Shao et al. [1993] suggested the \( F \propto u_*^3 \) and \( F \propto u_*^3 \) relationship, this study suggests a \( F \propto u_*^3 \) relationship. The exponent \( i \) can be larger than 3 and depends on soil conditions, especially soil hardness. Some secondary factors, such as surface roughness and soil moisture, also influence the \( F \) and \( u_* \) relationship.

4. Soil Erodibility and Plastic Pressure

For a given wind velocity, dust emission is determined by the capacity of the surface to release dust particles, which is largely affected by the physical and chemical properties of the soil [Zobeck, 1991]. It is well known, for instance, that surface crust and soil aggregation suppress wind erosion and reduce dust emission rate. Also, a high percentage of fine particles in a soil does not necessarily imply that the soil must be a strong dust source. Soils with more than 10% clay are, for example, not easily erodible unless the surface is broken up by mechanical disturbance. Sandy and loamy soils are usually more important dust sources because they are

![Figure 4](image-url)
less cohesive, although these soils have a small percentage of dust particles. The mechanical stability of the soil is therefore important.

Chepil and Woodruff [1963] defined the mechanical stability of a soil as the resistance of the soil to the breakdown by a mechanical agent, such as tillage, wind shear, or abrasion from aeolian particles. Mechanical stability depends largely on interparticle cohesion in the soil system. During wind erosion, saltating particles strike the soil surface and cause a certain amount of disruption around the impact point. The amount of disruption depends on the cohesiveness of the solid particles in the removed volume by bombardment. More precisely, it depends on the total interparticle tensile force presented in that volume of soil which is disturbed by the impact of the saltating sand grain. Chepil [1955] suggested that the modulus of rupture, a measure of the cohesive strength of dry briquettes, varied inversely with the diameter of the soil particles \( \sigma \propto \frac{1}{d^3} \).

On the basis of the same idea, Smalley [1970] suggested that soil erodibility can be measured in terms of its tensile strength that is related to the packing density, the coordinating number of the particle, and the interparticle bond strength. He showed that the tensile strength in a simple soil system to be inversely proportional to \( d^3 \). Both Chepil and Woodruff [1963] and Smalley [1970] suggest that very fine soils are less erodible than coarse soils. Rice et al. [1997] suggested that surface erodibility can be characterized by using a modulus of elasticity. Wind erosion tends to take place in dry, less cohesive soils that normally have small modulus of elasticity. The elasticity can be neglected for totally loose soil and only pure plasticity needs to be taken into account. Another frequently used indicator of soil erodibility is the aggregate content. It is found that the more dry the aggregate (< 0.84 mm) content, the less erodible the soil [Chepil and Woodruff, 1963; Gillette, 1977]. However, a precise measurement of soil erodibility is not yet available because of the difficult nature of the problem itself.

A common feature exists among the above mentioned measures of soil erodibility (soil cohesion, tensile strength, modulus of elasticity, and aggregate content). They are soil mechanical properties and closely linked to soil stress-strain relationships or yield conditions. However, there is a great diversity in the measurement of soil mechanical properties, such as those obtained in triaxial tests, and shear strength by vane tests, tensile strength by modulus of rupture tests, and compressive strength by penetrometer resistance tests. This is because for material like soil, there is no unique yield condition and the yield is a function of the test method and the forces imposed.

In our dust emission model, the horizontal component of plastic flow pressure \( p \) is a parameter that represents soil erodibility. It can be determined by using a needle type penetrometer with suitable penetration depth and well-controlled load and speed [Rice et al., 1997]. It is conventionally called soil penetrometer resistance (defined as the mean maximum penetration pressure (MMPP), or mean maximum force per unit area). This technique is originally derived for investigating the effect of soil surface strength on the seedling emergence and erosion caused by raindrop impact. For the case of saltation bombardment, particle size has an important effect when it is of the same order as the indent diameter. A decrease in grain size is accompanied by an increase in local soil strength as the dislocations generated by the indenter are blocked by the grain boundaries [Rice et al., 1997]. It is therefore critical to choose a suitable test indenter with a scale comparable to saltation particle size and with a load comparable to the stress brought by the saltators.

In section 3.1, we estimated \( p = 967.57 \text{ N/m}^2 \) for the unaggregated soil bed used by Rice et al. [1996a]. This value is comparable with the soil penetrometer resistance obtained by Rice et al. [1997] for the same soil texture with light spray fine-particle soil surface. They found that MMPP for sprayed surface falls between 1000 and \( 10^6 \text{ N/m}^2 \). The model estimated \( p \) is slightly lower than the lower limit of their estimates, which represents a situation when the dedicated crust soil surface by light spray is disturbed by previous penetration. Therefore, it is reasonable to believe that the estimated value \( p = 967.57 \text{ N/m}^2 \) is not too far from the true value of \( p \) for the original unaggregated soil.

In section 3.2, we estimated \( p \) for seven soils studied by Gillette [1977] and found that for sand and loamy sand soils, \( p \) is within the range of \( 10 \sim 25 \times 10^5 \text{ N/m}^2 \). These \( p \) values are comparable with the field measurement of surface MMPP of sandy soils by using a needle penetrometer [Callebaut et al., 1985] but are about 100 times larger than the values of modulus of rupture measured by Gillette [1988]. The modulus of rupture defined by Gillette [1988] is the force applied to break certain length and thickness of crust. For a given soil surface, measurements often show that the modulus of rupture (which is a type of tensile strength) can be 10 to 100 times smaller than penetrometer resistance (which is a type of compressive strength). However, the modulus of rupture is of the nature of macrohardness and is not measurable for loose, or weakly crusted soil surfaces. As wind erosion mainly occurs on loose soil surfaces, the modulus of rupture may have only limited use as an indicator of soil erodibility.

According to Rice et al. [1997] the soil surface penetrometer resistance (hence \( p \)) varies between \( 10^5 \text{ N/m}^2 \) for the light spray fine soil and \( 10^7 \text{ N/m}^2 \) for the deep wetted soil with the same texture contents. This shows that \( p \) is not only a function of particle size. Even larger variation exists for a wide range of soil types. Figure 5 shows the calculated crater volume versus impact velocity for four different values of \( p \), corresponding to loosely packed unaggregated, lightly sprayed then dried (two cases) and deep wetted then dried soil surface, which consists of the same fine particles (\( \leq 53 \mu m \)) [Rice et
Figure 5. Calculated crater volume versus particle impact velocity for four different values of \( p \), corresponding to loosely packed unaggregated, lightly sprayed then dried (two cases) and deep wetted then dried soil surfaces, which contain fine particles (<53 \( \mu m \)) [Rice et al., 1997]. The diameters of impact particle and impact angle are set to the average values \( d = 275 \mu m \) and \( \alpha = 13^\circ \), as indicated by Rice et al. [1997]. The values of volume removal for unaggregated soil and three average values of volume removal in relation to impact velocity, estimated from Rice et al. [1996a] experiment data, are also shown.

The average impact particle diameter \( d \) was 275 \( \mu m \) and the average impact angle \( \alpha \) was 13\(^\circ\). The measured values of crater volume removal versus impact velocity for unaggregated soil are retrieved from Figure 11 of Rice et al. [1996a]. The impact velocities are estimated from the kinetic energy lost to the bed by setting the ratio of ricochet to impact velocity equal to 0.57 of the mean value [Rice et al., 1996a]. Three average values of the volume removal in relation to impact velocity calculated from the Rice et al. [1996a] experiment data are also shown in Figure 5. It is shown clearly that \( p \) has a profound influence on dust emission rate.

It is noteworthy that the empirical relationships of field dust emission rate versus \( u_\ast \) are often derived by least squares regression for different soil texture and surface conditions, and thus large differences in \( p \) and large data scatter are inevitable. It is therefore dangerous to use such empirical relationships without considering their limitations.

The penetrometer resistance (or \( p \)) is directly related to interparticle bonding forces (or energy). Both of them are affected not only by the particle size but also by wetting and drying processes, as shown by Rice et al. [1997], by chemical or watersoluble material, and by the contents of organic material. Because it is very difficult to describe all the processes involved mathematically, theoretical investigation of soil strength properties has only been carried out for very simple, ideal cases. Although some qualitative insight in the mechanism of cohesion has been achieved by researchers in colloidal science, it is unlikely that the average values of these strength properties can be calculated with reasonable accuracy if all the processes are considered. Practically, these soil strength properties are obtained by experimental measurement for given conditions under specific requirement. Obviously, the measurement of \( p \) is easier than that of interparticle bonding forces (or energy).

5. Conclusions

In this paper, we have presented a new dust emission model based on the understanding that dust emission is mainly caused by saltation bombardment. The prediction of dust emission rate is achieved through modeling the ploughing process of individual saltating sand grains and the resulted volume removal of the surface soil. It has been found that the crater volume removal is proportional to the impacting particle velocity \( V \propto U^n \); the vertical dust emission rate is proportional to friction velocity, \( F \propto u_\ast^{n+1} \), with \( n \) being around 2 to 3. For practical purposes the vertical dust flux can be calculated using equation (23) or equation (24) for simplicity.

The theoretical prediction of dust emission rate is well supported by the field observations of Gillette [1977], Gillette and Walker [1977], and Nickling and Gillies [1989, 1993]. The analysis presented in this paper provides a clarification of the long-standing argument among researchers whether \( F \) is proportional to \( u_\ast \) [Shao et al., 1993] or to \( u_\ast^4 \) [Gillette and Passi, 1988]. The theory provides an explanation for the wide divergence of the power relationship between \( F \) and \( u_\ast \). It has been shown that soil surface strength (represented by penetrometer resistance) plays an important role in determining the velocity dependence of dust emission rate.

The good agreement of the new dust emission model with experimental data further demonstrates that the exact dislodgement mechanism of dust emission by saltation bombardment is indeed surface ploughing and cratering. It raises a question over the basic assumption made by energy-based dust emission models; namely, the energy of impact saltator lost to the bed is mainly used for rupture interparticle bonds of those ejected dust particles. It can be shown that the impacting energy is largely consumed by plastic deformation (plough-
ing, relocating grains and friction between grains). The fraction of energy used to rupture interparticle bonds is actually negligible.

We have pointed out that there is a fundamental difference in the forces involved in the entrainment of sand particles by wind and in the dust emission by saltation bombardment. Unlike sand saltation, dust emission is indirectly derived by wind force. It involves the relationship between wind and saltation as an intermediate process. The mechanism responsible for the breakdown of interparticle bonds by particle impact is fundamentally different from that responsible for the lift-up of sand particles by aerodynamic forces. While the threshold friction velocity \( u_{\text{th}} \) is the key parameter for characterizing the surface capacity to resist sand drift, the horizontal plastic flow pressure \( p \) which can be measured as surface penetrometer resistance, emerges as the most important quantity in characterizing the soil physical properties related to dust emission. It is predicted that the dust emission rate is inversely proportional to \( p^k \), with \( k = 1 \sim 1.5 \). For hard surfaces with a large \( p \), the dust emission rate is more likely to be proportional to \( u_{\text{th}}^3 \), while for soft surfaces with a small \( p \), the dust emission rate is more likely to be proportional to \( u_{\text{th}}^4 \). Because of the large variation in soil conditions, it is therefore not surprising that a large scatter exists when field measurements of dust emission rate are plotted against \( u_{\text{th}} \), and both \( F \propto u_{\text{th}}^3 \) and \( F \propto u_{\text{th}}^4 \) relationships are observed.

The new dust emission model does, however, have the following limitations: (1) In reality, especially for agricultural soils, dust particles are not only ejected by sand particles impacting the surface but also are released due to the breaking down of aggregates during saltation and impact. The latter dust emission mechanism is not considered in the present model. The combination of these two processes and the random nature of soil aggregates, microtopography (ripples and ridges that influence the local impact angle) make it difficult to precisely predict the dependency of dust emission rate on the impact velocity, (2) the ratio of the vertical and horizontal plastic pressure \( K \) and the contact area between the ploughing particle and the surface soil may vary during collision and cannot be precisely described, (3) because the elastic forces have been neglected in the model, it may not be suitable for highly crusted soil, for which the elastic strains are comparable with the plastic strains. The erosion behavior of crusted soil may not be the same as loosely packed soil surfaces, and additional parameters may be required in characterizing the soil physical properties which control dust emission, (4) it is expected that the surface deforming property (or \( p \)) will exhibit a large spatial heterogeneity and temporal variation, and \( p \) is more difficult to measure for practical purposes than parameters such as \( u_{\text{th}} \), (5) uncertainties may be introduced by parameter \( c_N \); the fraction of dust particles become suspended from the volume ejected by saltation bombardment. It is a function of interparticle forces and hard to estimate theoretically. It may increase with impact velocity according to several experimental observations [Gillette and Walker, 1977; Gomes et al., 1990; Alfaro et al., 1997].

Acknowledgments. This work is supported by Australia Research Council. The authors are grateful to G. H. McIntaish and K. Tews at Griffith University for providing us with the particle size distributions of several Australian soils. We also wish to thank two anonymous reviewers for their constructive comments which greatly improved this paper.

References


---

H. Lu and Y. Shao School of Mathematics, The University of New South Wales, Sydney 2052, Australia. (e-mail: Y.Shao@unsw.edu.au)

(Received July 12, 1998; revised January 4, 1999; accepted February 25, 1999.)