Particle Adhesion and Detachment in Turbulent Flows Including Capillary Forces

Goodarz Ahmadi, Shiguang Guo & Xinyu Zhang

To cite this article: Goodarz Ahmadi, Shiguang Guo & Xinyu Zhang (2007) Particle Adhesion and Detachment in Turbulent Flows Including Capillary Forces, Particulate Science and Technology, 25:1, 59-76, DOI: 10.1080/02726350601146432

To link to this article: http://dx.doi.org/10.1080/02726350601146432

Published online: 23 Jan 2007.
Particle Adhesion and Detachment in Turbulent Flows Including Capillary Forces

GOODARZ AHMADI
SHIGUANG GUO
XINYU ZHANG

Department of Mechanical and Aeronautical Engineering, Clarkson University, Potsdam, New York, USA

The effect of capillary forces on particle adhesion and removal mechanism in turbulent flows is studied. Different detachment theories are used and the increase of adhesion force by the capillary effect is included in the analysis. The criteria for incipient rolling and sliding detachments are evaluated. The sublayer and burst models, which account for the structure of turbulent near-wall flows, are used for evaluating the air velocity condition near the substrate. The critical shear velocities for removing particles of different sizes under different conditions are evaluated, and the results are compared with those obtained in the absence of the capillary force. Comparisons of the model predictions with the available experimental data are also presented.

Keywords adhesion, capillary force, particle, removal, resuspension, surface tension

Introduction

Adhesion of fine particles to surfaces and their removal are of great concern in semiconductor, pharmaceutical, and xerographic industries. Forces between solids are predominantly of attractive nature and cause adhesion of particles to each other and to surfaces. These forces become increasingly significant for fine particles because the particle adhesion force per unit mass increases sharply as the particle size decreases. It is indeed very difficult to remove fine particles smaller than 1 μm (Ranade, 1987; Mittal, 1988, 1989, 1991).

Reviews of particle adhesion and removal were provided by Krupp (1967), Visser (1972), Tabor (1977), Bowling (1985), and Berkeley (1980). Accordingly, the van der Waals force makes the major contribution to particle adhesion to a surface under dry conditions. Derjaguin (1934) was the first to consider the effect of contact deformation on particle adhesion. The so-called JKR adhesion model was developed by Johnson, Kendall, and Roberts (1971) and includes the effects of the surface energy and surface deformation. Using the Hertzian profile assumption and including the effects of surface, Derjaguin, Muller, and Toporov (1975)
developed a particle adhesion theory that now is referred to as the DMT model. More recent adhesion models were developed by Tsai et al. (1991a) and Maugis (1992).

Resuspension of particles was studied by a number of researchers. Corn (1961) and Corn and Stein (1965) measured the re-entrainment of particles from plane surfaces, where the importance of surface roughness and relative humidity was noted. Punjrathe and Heldman (1972) studied particle resuspension mechanisms through a series of wind tunnel experiments. Gillett et al. (1974), Makhonko and Rabotnova (1982), and Garland (1983) reported results concerning particle resuspensions from soil and grass surface. Healy (1977), Sehmel (1980), Smith et al. (1982), Hinds (1982), and Nicholson (1988) provided reviews of resuspension processes. Particle detachment mechanisms in turbulent flows were studied by Cleaver and Yates (1973), where a resuspension model based on turbulence bursts was developed. More recent models on particle resuspension processes were reported by Reeks and Hall (1988), Wen and Kasper (1989), Wang (1990), Masironi and Fish (1967), Tsai et al. (1991b), Soltani and Ahmadi (1994, 1995a,b), and Ibrahim et al. (2003). Influence of relative humidity on adhesion was discussed by Podczeck et al. (1997). Recently, direct atomic force microscopy (AFM) measurement of adhesion force was reported by Gotzinger and Peukert (2003a,b).

In this work, the effect of capillary force on particle adhesion to a surface is studied. It is shown that capillary force plays an important role in the adhesion process. The JKR adhesion model as well as the sublayer and the burst models for near-wall turbulent flows are used. The theories of rolling and sliding detachments are considered, the critical shear velocities for detaching various size particles according to different models are evaluated, and the results are compared with those obtained in the absence of the capillary force. The model predictions for glass particles on glass and steel substrates are compared with the available experimental data for dry and humid air conditions. The effect of lift force on rolling and sliding detachment mechanisms is also studied.

Adhesion Model

In this section, a brief summary of the JKR adhesion model used in this study is presented.

In the Johnson-Kendall-Roberts (Johnson et al., 1971) (JKR) model, the Hertz contact theory was modified by taking into account the surface energy effects and by allowing for the deformation of the particle and the substrate. Accordingly, a finite contact area forms and the radius of the contact circle, $a$, is given as

$$a^3 = \frac{d}{2K} \left[ P + \frac{3}{2} W_A \pi d + \sqrt{3 \pi W_A d P + \left( \frac{3 \pi W_A d}{2} \right)^2} \right] \tag{1}$$

where

$$K = \frac{4}{3} \left[ \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right]^{-1} \tag{2}$$

is the composite Young’s modulus. Here, $d$ is the particle diameter, $P$ is the applied normal load, and $\nu_i$ and $E_i$ are, respectively, the Poisson ratio and Young’s modulus of material $i$ ($i = 1$ or 2). In Equation (1),
\[ W_A = \frac{A}{12\pi z_o^2} \]  

is the thermodynamic work of adhesion, where \( A \) is the Hamaker constant and \( z_o \) is the minimum separation distance.

According to the JKR model, the pull-off force \( F_{po} \) is given by:

\[ F_{JKR}^{po} = \frac{3}{4} \pi W_A d. \]  

At the moment of separation, the contact radius is given by

\[ a = \frac{a_o}{4^{1/3}} = \left( \frac{3\pi W_A d^2}{8K} \right)^{\frac{1}{3}} \]  

where \( a_o \) is the contact radius at zero applied load given as

\[ a_o = \left( \frac{3\pi W_A d^2}{2K} \right)^{\frac{1}{3}}. \]

**Capillary Force**

In humid air, condensation of water vapor around the particle-substrate contact area forms a meniscus, as shown in Figure 1. The meniscus thus formed will add an additional capillary force, beyond the van der Waals force and it significantly enhances the adhesion between the particle and the substrate. The capillary force \( F_c \) is determined by the surface tension of water \( \sigma = 0.0735 \text{ N/m, at normal temperature} \), the particle diameter \( d \), the wetting angle \( \theta \) and the angle \( \alpha \) as shown in Figure 1. That is,

\[ F_c = 2\pi \sigma d [\sin \alpha \sin (\theta + \alpha) + \cos \theta]. \]  

\[ \text{Figure 1. Geometric features of a small spherical particle attached to a surface with a capillary force.} \]
The first term in Equation (7) is due to the surface force and the second term is a consequence of the sub-ambient pressure in the liquid meniscus.

The angle $\alpha$ is normally very small, and for small values of wetting angle $\theta$, the expression for the capillary force becomes (Ranade, 1987; Zimon, 1982)

$$F_c = 2\pi\sigma d. \tag{8}$$

A JKR type model for adhesion of particles in liquid does not exist. Here we assume that particles are deposited on the surface under dry condition and then a liquid meniscus forms due to vapor condensation on the particle-substrate contact; thus, a superposition of forces may be assumed. The total force needed to lift off the particle, then, is $F_{po} + F_c$, where $F_{po}$ is given by Equation (4).

**Detachment Models**

**Rolling Detachment Model**

Figure 1 shows the geometric features of a spherical particle that is attached to a plane surface. It can be seen that a meniscus is formed around the gap between the particle and the surface. It is assumed that water cannot enter the contact interface between the particle and the surface. According to Tsai et al. (1991b) and Soltani and Ahmadi (1994, 1995a), a particle will be detached when the external force moment about the point “O,” which is located at the rear perimeter of the contact circle, overcomes the resisting moment due to the adhesion force, $F_{po}$, and the capillary force, $F_c$:

$$M_t + F_t \left( \frac{d}{2} - z_o \right) + F_L d \geq (F_{po} + F_c)a \tag{9}$$

where $F_t$ is the total external force acting on the particle (e.g., the fluid drag force), $z_o$ is the relative approach between the particle and surface (at equilibrium condition), $M_t$ is the external moment of the surface stresses about the center of the particle, and $F_L$ is the lift force acting on a sphere resting on a substrate in linear shear flow, as given by Leighton and Acrivos (1985). In most practical cases, $z_o$ can be neglected and the critical force ratio becomes

$$\frac{F_t}{F_{po} + F_c} = \frac{a}{M_t + \frac{d}{2} + \frac{2F_t}{F_t}}. \tag{10}$$

**Sliding Detachment Model**

When the effect of the capillary force is included, the condition for sliding detachment of the particle becomes

$$F_t \geq k(F_{po} + F_c - F_L) \tag{11}$$

where $k$ is the coefficient of static friction for particle-surface interface.
Hydrodynamic Forces and Torques

The near-wall turbulent flow is dominated by vortical coherent structures and occasional bursts, which have profound effects on the particle detachment process. Here, the sublayer and burst models for particle resuspension in turbulent flows are briefly outlined.

Sublayer Model

The maximum velocity in the viscous sublayer near a wall generated by the axial and vortical flows is given as (Soltani & Ahmadi, 1994, 1995b)

\[ u_+^M = 1.1365y^+ \]  \hspace{1cm} (12)

where

\[ u_+^M = \frac{u_M}{u^*}, \quad y^+ = \frac{yu^*}{\nu}. \]  \hspace{1cm} (13)

Here, \( u^* \) is the critical shear velocity, \( \nu \) is the kinematic viscosity of air, and \( u_M \) is the maximum velocity. In Equations (12) and (13), superscript plus denotes the variables stated in wall units. That is, these variables are nondimensionalized with the use of \( u^* \) and \( \nu \). The fluid velocity at the mass center of a particle attached to a wall may be obtained from Equation (12). That is,

\[ u_M = 0.568d^+ \]  \hspace{1cm} (14)

where \( d^+ \) is the nondimensional particle diameter defined as

\[ d^+ = \frac{d u^*}{\nu}. \]  \hspace{1cm} (15)

Using Equation (14) in the expression given by O’Neill (1968) for the drag force acting on a sphere attached to a wall, it follows that

\[ F_t = \frac{2.9\pi\rho d^2 u^*^2}{C_c} \]  \hspace{1cm} (16)

where \( \rho \) is the fluid density, and the Cunningham factor is given as (Fuchs, 1964; Friedlander, 1977)

\[ C_c = 1 + Kn[1.257 + 0.4\exp(-1.1/\Kn)]. \]  \hspace{1cm} (17)

Here the Knudsen number is defined as

\[ \Kn = \frac{2\lambda}{d} \]  \hspace{1cm} (18)

where \( \lambda \) is the mean free path of air. The corresponding moment of the surface stresses with respect to particle centroid is given as

\[ M_t = \frac{1.07\pi \rho u^*^2 d^3}{C_c} \]  \hspace{1cm} (19)
where the Cunningham correction factor is also included, and $\rho$ is the density of the air.

For the velocity field given by Equation (19), the lift force acting on the particle in contact with the substrate, as obtained by Leighton and Acrivos (1985), is given as

$$F_L = \frac{0.744 \rho u^4 d^4}{\nu^2}.$$  \hspace{1cm} (20)

**Burst/Inrush Model**

The maximum instantaneous streamwise velocity experienced locally near the wall during the turbulent burst/inrush is given in wall units as (Soltani & Ahmadi, 1994, 1995b)

$$u^+_M = 1.72y^+.$$  \hspace{1cm} (21)

In this case, the total drag force acting on the particle becomes

$$F_t = \frac{4.38 \pi \rho d^2 u^{+2}}{C_c}.$$  \hspace{1cm} (22)

Similarly, the corresponding hydrodynamic moment and the Leighton-Acrivos lift force are given as

$$M_t = \frac{1.62 \pi \rho u^{+2} d^3}{C_c}.$$  \hspace{1cm} (23)

$$F_L = \frac{1.7 \rho u^{+4} d^4}{\nu^2}.$$  \hspace{1cm} (24)

**Particle Detachment**

Soltani and Ahmadi (1994) analyzed the minimum critical shear velocity for removing different size particles in the absence of the capillary force. In this study, the critical shear velocities for particle removal in humid air are evaluated.

**JKR Rolling**

Using the JKR adhesion model, the minimum critical shear velocity for particle rolling detachment including the capillary and the lift forces is given as

$$u^+_c = \left[ \frac{0.286 W^{1/3} A_{\Lambda}}{\rho K^{1/3} \pi^{2/3} d^{4/3}} \left[ \pi (0.75 W_{\Lambda} + 2\sigma) - \frac{0.744 \rho d^4 u^4}{\nu^2} \right] \right]^{1/2}.$$  \hspace{1cm} (25)

for the sublayer flow model, and

$$u^+_c = \left[ \frac{0.188 W^{1/3} A_{\Lambda}}{\rho K^{1/3} \pi^{2/3} d^{4/3}} \left[ \pi (0.75 W_{\Lambda} + 2\sigma) - \frac{1.7 \rho d^3 u^{+4}}{\nu^2} \right] \right]^{1/2}.$$  \hspace{1cm} (26)

for the burst/inrush flow model.
**JKR Sliding**

Using the JKR adhesion theory, the critical shear velocity for sliding detachment is given as

$$ u_s^* = \left[ \frac{\pi k(0.75W_A + 2\sigma) - 0.744k\rho d^3 u_s^*/\nu^2}{2.9\pi \rho d/C_c} \right]^{1/2} $$  \hspace{1cm} (27)

for the sublayer flow model, and

$$ u_s^* = \left[ \frac{\pi k(0.75W_A + 2\sigma) - 1.7k\rho d^3 u_s^*/\nu^2}{4.38\pi \rho d/C_c} \right]^{1/2} $$  \hspace{1cm} (28)

for the burst/inrush flow model.

**Results**

In this section, the results are presented and discussed. Table 1 shows the properties of the material used in this study.

Particles will be removed from the surface if the shear velocity is larger than the critical value, $u_s^*$, as derived in the previous section. Variations of $u_s^*$ for the rolling detachment of a silicon particle from a silicon substrate under humid and dry air conditions as predicted by the JKR adhesion model are shown in Figure 2. It is observed that the presence of the capillary force significantly increases the critical shear velocity needed for rolling removal. Furthermore, the magnitude of $u_s^*$ estimated from the sublayer flow model is higher than that for the burst/inrush flow model.

Variations of $u_s^*$ for sliding detachment under dry and humid air conditions as predicted by the JKR adhesion model are shown in Figure 3. The trend of variation is similar to those obtained in Figure 2. The critical shear velocity decreases as the

<table>
<thead>
<tr>
<th>Table 1. Material properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material/substrate</td>
</tr>
<tr>
<td>Copper-copper</td>
</tr>
<tr>
<td>Glass-glass (dry)</td>
</tr>
<tr>
<td>Glass-glass (moist)</td>
</tr>
<tr>
<td>Glass-steel</td>
</tr>
<tr>
<td>Polystyrene-polystyrene</td>
</tr>
<tr>
<td>Calcium carbonate-calcium carbonate</td>
</tr>
<tr>
<td>Aluminum oxide-aluminum oxide</td>
</tr>
</tbody>
</table>
particle diameter increases, and the capillary force enhances the particle adhesion significantly. Comparing Figures 2 and 3, it is observed that the critical shear velocities for sliding removal are much higher than those required for rolling detachment.

Figures 4 and 5, respectively, show variations of the critical shear velocity with particle diameter for detachment of polystyrene particles from a polystyrene substrate with rolling and sliding mechanisms as predicted by the sublayer and burst/inrush resuspension models. Both cases are also analyzed when capillary forces are present or absent. These figures show that the critical shear velocities decrease with increase of the particle diameter. Furthermore, the presence of the capillary force dramatically increases the critical shear velocity for particle removal. The critical shear velocities for sliding removal are also much higher than those for rolling detachment. Comparison of Figures 4 and 5 reveals that the critical shear velocities predicted by the sublayer model are higher than those predicted by burst/inrush model. Compared to Figures 2 and 3, Figures 4 and 5 show much lower critical shear velocities. This implies that the polystyrene particles are much easier to remove from a polystyrene substrate than copper particles from a copper substrate.

The critical shear velocities for removal of calcium carbonate particles from a calcium carbonate substrate with rolling and sliding mechanisms as predicted by the sublayer and burst/inrush resuspension models, respectively, are shown in Figures 6 and 7. The effect of the presence of capillary forces is also shown in these figures. The general trends are similar to those of Figures 2–5. That is, larger particles are easier to remove and the capillary force significantly increases the adhesion

![Graph Image](image-url)
Figure 3. Variation of the critical shear velocities with particle diameter for resuspension of copper particles from a copper substrate with and without capillary forces, as predicted by the sliding detachment mechanisms and the JKR adhesion model.

Figure 4. Variation of the critical shear velocities with particle diameter as predicted by the sublayer model and the JKR adhesion theory for resuspension of polystyrene particles from a polystyrene substrate with and without capillary forces.
Figure 5. Variation of the critical shear velocities with the particle diameter as predicted by the burst model and the JKR adhesion theory for resuspension of polystyrene particles from a polystyrene substrate with and without capillary forces.

Figure 6. Variation of the critical shear velocities with particle diameter as predicted by the sublayer model and the JKR adhesion theory for resuspension of calcium carbonate particles from a calcium carbonate substrate with and without capillary forces.
force. Spherical particles are more easily removed by rolling detachment mechanism than sliding. Comparison of Figures 6 and 7 reveals that the critical shear velocities predicted by the sublayer model are higher than those predicted by the burst/inrush model. Comparison of Figures 2–7 shows that, when capillary forces are present, the critical shear velocities for removal of calcium carbonate and polystyrene are about the same. In the absence of the capillary force, the critical removal shear velocities for removal of calcium carbonate are significantly larger than those for removal of polystyrene particles. It is also seen that the increase of the critical shear velocities due to capillary effects is more significant for polystyrene particles than for calcium carbonate particles.

Figures 8 and 9 show variations of the critical shear velocity with particle diameter for detachment of aluminum oxide particles from an aluminum oxide substrate, with and without capillary effects. Similar to the results with polystyrene and calcium carbonate particles, these figures show that the critical shear velocities decrease with increase of the particle diameter; the capillary force dramatically increases the critical shear velocity, and the critical shear velocities for sliding removal are much higher than those for rolling detachment. Comparison with Figures 2 and 3 for copper particles shows that aluminum oxide particles can be removed at much lower critical shear velocities. When capillary forces are present, the critical shear velocities for removal of aluminum oxide particles are comparable to those for calcium carbonate and polystyrene particles. For different materials and in the absence of capillary forces, the critical shear velocities for particle removal are, however, quite different.

Figure 7. Variation of the critical shear velocities with the particle diameter as predicted by the burst model and the JKR adhesion theory for resuspension of calcium carbonate particles from a calcium carbonate substrate with and without capillary forces.
Figure 8. Variation of the critical shear velocities with particle diameter as predicted by the sublayer model and the JKR adhesion theory for resuspension of aluminum oxide particles from an aluminum oxide substrate with and without capillary forces.

Figure 9. Variation of the critical shear velocities with particle diameter as predicted by the burst model and the JKR adhesion theory for resuspension of aluminum oxide particles from a aluminum oxide substrate with and without capillary forces.
Comparison with Experimental Data

Comparisons of the model predictions with the experimental data of Taheri and Bragg (1992) and Zimon (1982) are performed in this section. The experiment of Taheri and Bragg was concerned with the resuspension of glass particles from a smooth glass surface for a range of air velocities between 2 and 130 m/s. The experiments of Zimon (1982) were for the entrainment of glass particles from a steel substrate.

Figures 10 and 11 show variations of the critical shear velocity with particle diameter for glass particles according to rolling and sliding detachment mechanisms as predicted, respectively, by the sublayer and burst/inrush resuspension models. Here the JKR adhesion theory is used, and the cases where the capillary force is present or absent are treated. For glass particles in moist air, Visser (1976) reported an estimated value for the effective Hamaker constant of $A = 320 \times 10^{-20}$ J. The critical shear velocities using this estimated Hamaker constant are also shown in these figures. It is observed that the experimental data of Taheri and Bragg for removal of 25 μm and 42 μm glass particles under humid air is in good agreement with the model predictions for rolling detachment in the presence of capillary force. Moreover, it is observed that the predictions using the estimated effective Hamaker constant are higher than those of the experimental data. This implies that the effective Hamaker constant suggested by Visser (1976) overestimates the critical shear velocity. Comparing Figures 10 and 11 shows that the values of $u^*$ as evaluated from the burst/inrush model are somewhat lower than those of the sublayer model.

![Figure 10](image_url)

**Figure 10.** Comparison of the critical shear velocities as predicted by the sublayer model and JKR adhesion theory with the experimental data of Taheri and Bragg (1992) for resuspension of glass particles from a glass substrate with and without capillary forces.
Variations of critical shear velocities with the particle diameter for detaching glass particles from a steel substrate according to the rolling and sliding detachment mechanisms as predicted by the sublayer and burst/rush flow models are shown in Figures 12 and 13 respectively. The experimental data of Zimon (1982) are also reproduced in these figures for comparison. The JKR adhesion theory is used in these analyses. It is observed that the experimental data are lower than those predicted using rolling and sliding models under both dry and humid air conditions. As noted by Soltani and Ahmadi (1995a), this may be due to the surface roughness, which can reduce the particle adhesion force significantly. Comparing Figures 12 and 13, it is observed that predictions of the burst model for $u_c$ are lower than those of sublayer model.

**Effects of Lift Force**

To study the effects of lift force on rolling detachment mechanism, the critical shear velocities are evaluated for the cases when the lift force is present and absent. The JKR adhesion model with the capillary force is used in these analyses. Figure 14 shows the corresponding variations of the critical shear velocities with particle diameter. Here the rolling detachment mechanism in the presence of the capillary force is used. It is seen that the critical shear velocities for the case with or without lift force are almost the same. This implies that the effect of lift force on the rolling detachment is very small and can be neglected.
Figure 12. Comparison of the critical shear velocities as predicted by the sublayer model and the JKR adhesion theory with the experimental data of Zimon (1982) for resuspension of glass particles from a steel substrate with and without capillary forces.

Figure 13. Comparison of the critical shear velocities as predicted by the burst model and JKR adhesion theory with the experimental data of Zimon (1982) for resuspension of glass particles from a steel substrate with and without capillary forces.
Conclusions

Particle resuspensions, including the effect of capillary force using different adhesion theories and detachment models in turbulent flows, are studied. The effect of the near-wall lift force of Leighton and Acrivos is also included in the analysis. Analytical expressions for the critical shear velocities for particle removal are obtained and the results are presented in graphical form. On the basis of the presented results, the following conclusions are drawn:

- The capillary effect significantly enhances the particle adhesion force, and the critical shear velocity for particle detachment increases accordingly.
- Rolling is the dominant detachment mode for spherical particles in the presence (or absence) of capillary force.
- The burst/inrush flow model leads to lower values of critical shear velocity for particle removal when compared with the sublayer flow model.
- The effect of lift force on particle detachment is very small and could be neglected.

References


Cleaver, J. W. & B. Yates. 1973. Mechanism of detachment of colloidal particles from flat sub-
strate in a turbulent flow. J. Colloid Interface Sci. 44: 464–474.
Corn, M. 1961. The adhesion of solid particles to solid surfaces. II. J. Air Pollut. Control
Assoc. 11: 566–575.
Assoc. 26: 325–336.
Derjaguin, B. V. 1934. Untersuchungen über die Reibung und Adhasion, IV. Theorie des
Anhaftens kleiner Teilchen. Kolloid Zh. 69: 155–164.
Derjaguin, B. V., V. M. Muller, & Yu. P. Toporov. 1975. Effect of contact deformation on the
Garland, J. A. 1983. Some recent studies of the resuspension of deposited material from soil
and grass. In Precipitation Scavenging, Dry Deposition and Resuspension, vol. 2, ed. by
1097.
distributions of aerosols generated by the wind erosion of soils. J. Geophys. Res. 79: 4068–
4075.
Gotzinger, M. & W. Peukert. 2003b. The influence of particle charge and roughness on par-
Healy, J. W. 1977. A review of resuspension models. In Transuranics in Natural Environments,
ed. by M. G. White and P. B. Dunaway. NVO-178. Las Vegas, Nev.: U.S. Dept. of
Energy. pp. 211–222.
exposed to turbulent air flow: Controlled experiments and modeling. J. Aerosol Sci. 34:
765–782.
Johnson, K. L., K. Kendall, & A. D. Roberts. 1971. Surface energy and contact of elastic
140.
Leighton, D. & A. Acrivos. 1985. The lift on a small sphere touching a plane in the presence of
surface and particulate contamination of vegetative cover. Pure Appl. Geophys. 120: 54–
66.
Masironi, L. A. & B. R. Fish. 1967. Direct observation of particle re-entrainment from sur-
Plenum.
Plenum.
Plenum.


