Saltation and Suspension of Particulate Matter in Air

Final Report

Peter K. Haff and Robert S. Anderson

August 1989

U.S. Army Research Office

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A summary of progress which has been made on the computer simulation and modeling of wind blown sand transport is included.

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Progress has been made along several fronts in our research on saltation and suspension. We report briefly here on several of these research areas.

1) B.T. Werner has recently completed a set of two-dimensional simulations of saltation impacts with a granular bed. The results of the simulations show striking similarities with actual impact experiments (see item #5) using medium coarse sand: the ejecta typically include a high energy rebound of the incident particle, and several low energy particles. The distributions of the ejection velocities, as functions of the impact velocity, form the basis of the "splash function" needed to characterize the grain-bed interaction, and to close the saltation problem. Werner has recently submitted this work for publication in Sedimentology.

2) We have begun to consider the role of wind fluctuations in sediment transport by wind. Most mass flux "laws" are derived from experiments performed in wind tunnels that necessarily have a truncated form of wind velocity spectra. Our preliminary calculations demonstrate that the application of such flux relations to the real world, characterized by a wide spectrum of wind velocities, inevitably lead to underestimates of flux, sometimes by more than an order of magnitude. This arises from the inherent non-linearity of such mass flux relationships (typically, the mass flux is taken to be proportional to the cube of the shear velocity); the existence of a threshold shear velocity, below which no mass flux occurs, adds to the effect, making flux predictions at low shear velocities extremely inaccurate. We are currently initiating collaboration with researchers in England (Graham Butterfield), and in Denmark (Michael Sorenson, at Aarhus), who have collected realistic spectra of wind velocity fluctuations both in the fielld and in wind tunnel settings. It is our conviction that much of the discrepancy between the relationships reported for various wind tunnels may be accounted for by differing turbulence characteristics of the tunnels, and that considerable attention must be paid to fluctuations at all scales in the real world settings in which we ultimately want to be able to predict mass fluxes.

3) R.S. Anderson is close to completing a manuscript on the structures of the grainfall deposits to be expected in the lee of eolian dunes. Geologists seeking to infer depositional settings from fossil dune deposits have been seriously hampered by the lack of a quantitative model of grainfall deposition. We may now predict the pattern of grainfall deposition as a function of wind velocity and grainsize. The pattern of deposition rate displays a maximum within one to two decimeters of the dune brink, beyond which it falls off roughly exponentially, the exponent being dependent in a simple way on both grain size and wind velocity. A characteristic length scale emerges (essentially the inverse of the exponent), which may help predict at what point on the lee slope of a dune

the process of grainfall will give way to that of grainflow. It is demonstrated that only under rare circumstances (e.g. very fine particles) should the pattern of grainfall deposition be such that the dune may migrate forward without the oversteepening that gives rise to grainflow avalanches. This length scale should also aid in inferring from the fossil record the heights of the original dunes, which are inevitably truncated in the process of preservation. R.S. Anderson presented these results recently at the 17th Annual Binghamton Symposium on Geomorphology, held in Guelph, Ontario, sparking considerable interest in G. Koceruk, a stratigrapher and sedimentologist at U. Texas at Austin. Future collaboration with Koceruk is anticipated in this and other applications of available eolian sediment transport theory to the fossil record. In addition, a preliminary field effort has been made to collect more detailed data on the pattern of deposition rate, using a recently reported shadow / photographic technique. The method reveals subtleties in the pattern that were missed in previous reports. Further measurements are anticipated to test more rigorously the dependences on wind velocity and grain size predicted by the theory.

4) R. S. Anderson and P.K. Haff are refining the model for the dispersal of saltating grains across a rough, immobile surface. The manuscript should be completed shortly. Current work on gustiness (item #2) should also allow for treatment of fluctuations in wind direction, which, along with the bed collision process, will lead to dispersal. Of interest will be the relative roles of these two processes in the dispersal of various grain sizes.

5) B.T. Werner has recently succeeded in photographing the impacts of individual sand grains with a sand surface, using the "sand gun" capable of accelerating sand grains to several meters per second. The resulting photographs resolve not only the impact and ejection velocities, but also grain rotations. Experiments at various impact angles and speeds, into mono-sized sand beds will allow construction of a realistic splash function necessary for the full saltation calculations. Similar experiments with a mixed bed should provide insight into not only the mixed saltation case, but the all-important coupling between the saltation process and the ejection of grains small enough to be put into suspension.

6) The attendance of R.S. Anderson at the Guelph meeting has initiated several possible collaborations. (i) Subsequent correspondence with W.G. Nickling (at U. Guelph), who has recently developed the most sophisticated techniques to date for measuring the ejection rate of saltating grains from the bed, has allowed us to request particular experiments that will allow significant testing of predictions made from our theoretical models of saltation. (ii) Brian Willetts (U.Aberdeen, Scotland) has suggested future collaboration. As Dr. Willetts is currently the frontrunner in

producing high-speed motion pictures of the full saltation process, from which splash functions may also be extracted; such interchange ought to be productive from the standpoint of both groups. (iii) The visit to Caltech of Michael Sorenson (U. Aarhus, Denmark) after the Guelph conference provided considerable opportunity for discussion of our parallel approaches to the theory of eolian saltation. In addition, his work on eolian suspension has followed closely that of R.S. Anderson, who suggested to the Aarhus group the use of a modified form of the langevin equation in a visit to Denmark in late 1985. Further collaboration on the suspension problem is anticipated, as well as the exchange of gustiness data mentioned in item #2.

7) In mid-September, B.T. Werner visited the group of researchers at A.S.U. Tempe led by Ron Greeley, to whom he presented his work on the simulation of the full saltation problem. Discussion was lively, the point of the important role of saltation impacts being demonstrated forcefully.

8) Dr. Mike Malin of Arizona State University in Tempe visited Caltech in mid-November in order to consider collaboration on several eolian topics of mutual interest. His focus in the past has been on the collection of wind erosion data from natural settings in Iceland and Antarctica, a phenomenon we are in a position to model. He has provided access to his extensive data sets in exchange for aid in calculation of particle trajectories he needs for simulation studies he is carrying out.

9) In an article recently accepted for publication in Sedimentology, R.S. Anderson suggested that the wavelengths of eolian impact ripples should be several times longer than the typical "reptation length" -- the hop length of those low-energy ejecta typically resulting from high-energy saltation impacts. These results were presented at the Geological Society of America annual meeting in San Antonio in mid-November, and in a more extensive, invited talk, at the Gilbert Club (Theoretical Geomorphologists) meeting in Berkeley in mid-December. Additional discussion with colleagues in general sediment transport and in eolian sediment transport in particular was fostered by R.S.Anderson's visit to the University of Washington campus in early December, and his attendance at the Luna B. Leopold symposium at the American Geophysical Union meeting in San Francisco just prior to the Gilbert Club meeting.

The Impact Process in Eolian Saltation: Two-Dimensional Studies

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ABSTRACT

A critical event in the trajectory of a sand grain saltating in air is its interaction with the surface. We examine the phenomenon of grain-bed impacts in two dimensions using a combination of dynamical simulations, analytical models and physical reasoning. The results indicate that the grain-bed collisions can be treated as two-body collisions with the bed particle assuming an effective mass greater than its true mass. Also, the presence of geometrical surface irregularities has a strong bearing on the interaction between saltating and bed populations, as well as on the formation of small-scale bedforms.

Steady State Saltation in Air

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ABSTRACT

Coupled equations of motion for steady state saltation over an infinite plane are derived and solved for a simplified model of the grain-surface impact process. Experimentally observed features of the wind velocity profile in saltation are qualitatively reproduced, including a diminution of the sub-saltation layer mean wind speed, as the friction speed increases. In this model the surface impact velocity of the saltating grains remains relatively constant over a wide range of free-stream shear stresses, and the grain mass flux increases with friction speed u_f^* less rapidly than u_f^{*3}.

EOLIAN SEDIMENT TRANSPORT AS A STOCHASTIC PROCESS: THE EFFECTS OF A FLUCTUATING WIND ON PARTICLE TRAJECTORIES

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ABSTRACT

Particle response to turbulent velocity fluctuations of the wind may be characterized by a response time that is strongly dependent upon grain diameter. While very small particles respond quickly to all wind velocity fluctuations, and follow essentially fluid element paths, larger particles respond only to the lower frequency air velocity fluctuations, and hence diverge significantly from fluid element paths. A realistic model of the history of the wind velocity fluctuations to which an airborn particle is subjected, incorporating both the vertical structure of the turbulence in the atmospheric boundary layer, and the effects of particle "slip" relative to the air, combined with a simple linear differential equation for the particle response to step changes in wind velocity, allows calculation of suspension trajectories. Ensembles of such trajectories produce concentration profiles that compare favorably with power-law concentration profiles predicted using continuum suspension theory. The same fluctuation field acts to modify trajectories of larger particles previously modelled as being determined entirely by the mean wind profile, the modifications diminishing as particle size increases. The spectrum of particle behavior is therefore shown to be continuous, with saltation and suspension its idealized end-members.

A THEORETICAL MODEL FOR EOLIAN IMPACT RIPPLES

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ABSTRACT

New insights into the grain-bed impact process arising from both numerical and physical experiments involving single grain impacts lead to a more complete conceptual model of eolian saltation process that in turn allows a simple model of eolian impact ripples to be developed. The saltating population may be idealized as consisting of (1) long trajectory, high impact energy, constant impact angle "successive saltations", and (2) short trajectory, low impact energy "reptations". It is argued that the spatial variations in mass flux due to the reptating population lead to the growth and translation of impact ripples.

Using the sediment continuity equation, an expression for the spatial variation in the ejection rate of reptating grains from a sinusoidally perturbed bed, and a probability distribution for the reptation lengths, a simple stability analysis demonstrates that the flat bed is unstable to small amplitude perturbations. A fastest-growing wavelength emerges that is roughly six times the mean *reptation* length, and is only weakly dependent upon the detailed shape of the probability distribution of reptation lengths. The results match well with field and wind tunnel observations of initial ripple wavelengths, and argue strongly against the widely held view, initially espoused by Bagnold, that ripple wavelengths are equal to the mean *saltation* length.

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BRIEF OUTLINE OF RESEARCH FINDINGS

See attached sheets

We report here on progress made along several of the lines of research established during the last reporting period, and comment on a few new directions taken.

1) B. T. Werner has completed his Ph.D. dissertation entitled A Physical Model of Wind-Blow Sand Transport. This work provides a detailed description of grain dynamics simulations and of the impact process in aeolian saltation. It generalizes previous work of Ungar and Haff on steady-state saltation by treating the grain-bed interactions in a more realistic fashion. The evolution of the sand surface under saltation is studied in detail, including the development of a novel model of ripple motion and stability. Computer simulation results were shown to compare favorably with the results of laboratory and field experiments.

2) R. S. Anderson has completed his manuscript on the pattern of grainfall deposition to be expected in the lee of eolian dunes. This has recently been accepted for publication in Sedimentology. Please see attached abstract.

3) R. S. Anderson is now preparing a manuscript on the role of wind variability in saltation flux measurement. By combining simulations of wind velocity histories with a simple mass flux "law" that incorporates a response time to changes in wind velocity, simulated mass flux histories are produced. The total flux over a specified period of time, taken to be much larger than the expected response time of the saltation system, is then contrasted with the flux calculated from application of the mass flux law using only the mean wind velocity over the time period, as is typically done in wind tunnel and natural world measurements. Because of the nonlinearity of mass flux as a function of the shear velocity of the wind, the calculated fluxes with a realistically variable wind are greater than those calculated using only the mean wind. The differences depend on the mean wind speed, the response time of the saltation system, and the correlation structure of the wind velocity history. W. G. Nickling has agreed to make measurements in his wind tunnel that ought to pin down the response time of the saltation flux to changes in the wind velocity. M. Sorenson, of Aarhus University, has provided data from a field experiment in Denmark that will allow checking of the wind velocity history simulations.

4) Considerable effort was put into trying to understand the evolution of ripple patterns through time during eolian saltation. Earlier analytical work of R. S. Anderson had established that a flat bed was unstable to small perturbations, and that a preferred initial wavelength emerges. Breakdown of that analysis for finite disturbances led naturally to numerical simulations. Particle impacts at a specified angle produced granular splashes characterized by the number of ejected grains and their ejection velocities, to be chosen from a given probability distribution. Mean ripple wavelengths and amplitudes are seen to grow through time, as is indeed observed in Nature. It has also been found useful to follow the development of the power spectral density of the resulting topography through time, a useful discriptor of the surface that has also been measured from shadow photographs made in the field. A further refinement of the splash function should allow treatment of the granular sorting one sees in typical eolian ripples.

Ripple studies via computer simulation were also reported by B. T. Werner in his thesis.

5) Simulations of two-dimensional granular surfaces using a code developed by P. K. Haff have provided the basis for new thinking about several problems related to saltation transport.

We can now look quantitatively at the distribution of angles seen by a particle of a given size as it impacts the bed, a distribution that influences strongly its rebound angle. As the size of the impacting particle becomes larger than the mean grain size of the bed, the surface begins to look flatter; the distribution of ejection angles ought therefore to become more tightly peaked, and centered around the angle of incidence.

We can artificially shadow the surface, the percentage of the surface in shadow being a strong function of the angle of illumination. We are currently exploring the possibility of having microtopographic profiles made from stereo pairs of photographs of natural granular surfaces in order to check on the relevance of the two-dimensional simulations. This would also more directly constrain the impact rule used in assessing the dispersion of saltating grains across such a surface, a model of which we have in hand.

The roughness of natural surfaces is also being investigated where the grain sizes are large enough to allow topographic profiling. Measurements of the power spectra from topographic profiles of alluvial fan surfaces of various ages in the Panamint Valley, made in January, provided a starting point for thinking about the evolution of such surfaces. R. S. Anderson has since initiated a collaborative effort with Tom Farr of JPL to address the roles of various processes in controlling the evolution of these spectra through time.

6) We anticipate the beginning of a preliminary investigation of the landscape erosion caused by the test-firing of the Shuttle Solid Rocket Booster at the site near Brigham City, Utah. Wind velocities obtained in the hot jet are sufficient to cause significant erosion for over half a mile from the test pad. We have obtained permission from the Morton-Thiokol management to perform topographic profiling before and after the next test (scheduled for early-mid August 1987), and to make qualitative observations of the entire array of erosive phenomena. We expect this well-controlled extreme experiment to lend insight into the erosive effects of very high winds associated with volcanic explosions such as that on Mt. St. Helens, with military operations such as testing and detonation of explosive devices, and with rare atmospheric events both here on Earth and other planets.

Submitted to Sedimentology

THE IMPACT PROCESS IN EOLIAN SALTATION: TWO-DIMENSIONAL STUDIES*

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ABSTRACT

A critical event in the trajectory of a sand grain saltating in air is its interaction with the surface. We examine the phenomenon of grain-bed impacts in two dimensions using a combination of dynamical simulations, analytical models and physical reasoning. The results indicate that the grain-bed collisions can be treated as two-body collisions with the bed particle assuming an effective mass greater than its true mass. Also, the presence of geometrical surface irregularities has a strong bearing on the interaction between saltating and bed populations, as well as on the formation of small-scale bedforms.

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Sedimentology, in press

THE PATTERN OF GRAINFALL DEPOSITION IN THE LEE OF EOLIAN DUNES

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ABSTRACT

A simple model for the deposition pattern in the lee of eolian dunes is presented that relies heavily upon a recently developed understanding of eolian saltation. Grainfall deposition at any position on the lee face is the result of all saltation trajectories that leave any point on the surface of the dune upwind of the brink with sufficient initial velocity to travel the intervening distance. The deposition rate at any position on the lee slope is obtained by integrating over all combinations of initial position and required velocity, the velocity being weighted by its probability density.

The resulting calculated total deposition rate patterns show distinct maxima on the order of one to a few decimeters from the brink, beyond which deposition rates fall off roughly exponentially. An important length scale emerges that characterizes this decay with distance from the brink, the length increasing with wind velocity, and decreasing with grain diameter. It is shown that this length scale is on the order of one meter for typical grain size and wind conditions. That this is typically smaller than the length of the lee slope is what gives rise to the oversteepening and eventual avalanching of the lee sides of eolian dunes. The position of a pivot point on the lee slope may be predicted, separating source regions from accumulation regions for grainflow avalanche deposits.

The calculated patterns provide not only a means for quantitative interpretation of active and fossil dune grainfall deposits, but they provide the initial geometry for grainflow avalanches. The initial failures should coincide with the steepest gradient in grainfall deposition, slightly downslope from the grainfall maximum.

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BRIEF OUTLINE OF RESEARCH FINDINGS

Significant progress has been made along several parallel lines of attack on related eolian problems, ranging from the simulation of grain impacts with a natural rough sandy surface, simulation of the approach of the eolian saltation to steady state, measurement of natural sand bed roughness, and measurement of the dramatic landscape alterations caused by the test firing of the space shuttle's solid rocket booster. These research efforts have led to the advancement of two collaborative projects that promise to yield substantial benefits within the year.

Simulations are currently being carried out to study the effect of grain impacts on irregularly packed particle beds, i.e., to compute numerically the "splash function". These surfaces resemble more closely natural sand surfaces than do the regular hexagonal packings used in earlier simulation work. One preliminary result is a de-emphasis of the importance of "brink" particle contributions to the ejected population. The current simulations use particles of radius 0.5mm, an improvement over earlier work, in which 1cm radius "sand" grains were used, the results being normalized by scaling arguments to apply to sand-sized material. The simulation of true sand-sized particles comprises a more intensive use of computer resources because of small time-step requirements needed to minimize particle overlaps. We attempt to keep the computing equipment supplied under the present ARO grant running around the clock as part of our effort to map out in detail the behavior of the splash function.

Simulations described above (carried out by PKH) are now being compiled (by RSA) to establish a complete representation of the splash function needed for the full simulation of the saltation process discussed below. Importantly, the impact computations will fill in major gaps in the splash function. To date, the splash function has been constrained by physical single grain impact experiments performed by B.T. Werner, by photography during wind tunnel saltation performed by B.B. Willetts (in Aberdeen, Scotland), and by earlier computations using regular hexagonal particle lattices done by B.T.Werner. Missing especially is data at low impact velocities. In addition, extension of our current computations to the multiple grain-size case will be straight-forward. This will be done as soon as the splash function for single grain sizes is completed.

Significant progress has been made in the full simulation of saltation carried out with the available splash function data. Full simulation includes calculation of (1) aerodynamic entrainment of grains from the bed (taken to first order as being linearly dependent on the excess shear velocity), (2) grain trajectories, (3) grain impact (using the splash function, represented by a splash matrix), and (4) the feedback in which the wind velocity profile is altered by the extraction of momentum by saltating grains. The sole initial conditions in the model are the grain diameter and the initial wind velocity profile, taken to be logarithmic with an imposed shear velocity and surface roughness. We make use of a "collision list" algorithm developed in the simulation of electron transport through metals to keep track of the times at which particular trajectories are expected to impact the bed, and hence when the resulting granular splash should be calculated. This alleviates problems attendant to the fact that particle trajectory times vary over two orders of magnitude, and makes the simulated time evolution of the saltating population much more realistic.

Initial results of this modelling are encouraging. The mass flux shows roughly the dependence on shear velocity expected from wind tunnel experiments (crudely cubic in shear velocity). The time scale for the development of steady state saltation is on the order of 1-2 seconds, and appears to be dependent upon the shear velocity, lower shear velocities corresponding to longer response times. These results are intuitively appealing in that the response time should be several hop times of the more energetic grains.

These estimates of the response time will allow completion of a project started a year ago in which we set out to determine the role of wind velocity fluctuations on mass flux. Importantly, the saltation system will respond entirely to all fluctuations with periods much greater than this response time. As natural winds are highly variable on all time scales, predicting fluxes by using winds averaged over periods of many minutes to many hours -- a practice common in the sedimentology and geomorphology literature -- may significantly underestimate the actual flux.

We intend to assess quantitatively the expected discrepancy, and to test our modelled fluxes against the available data that allows comparison between mass fluxes measured in wind tunnels and natural winds.

We have recently received word that we and Brian Willetts, at the University of Aberdeen, Scotland, have been awarded a N.A.T.O. travel grant to foster collaboration between the two groups. The grant will support several trips of each group to visit the other over a 2-3 year period. Our first meeting will be held in Tempe, Arizona in late March 1988.

Our earlier progress in measuring and modelling natural surface roughnesses of natural surfaces has now focussed on two aspects. First, as roughness at the grain level is important in affecting the number and distribution of ejecta from grain impacts, our current simulations of the impact process involve calculations using three separate realizations of a rough bed. Second, we have also measured natural sand bed roughness using a stereopair technique adapted by T.G. Farr at the Jet Propulsion lab, with whom collaborative efforts to quantify the interaction of surface processes and surface morphology of alluvial fans and volcanic flows in arid regions are continuing.

Although the project to address the modification of the landscape caused by the test firing of the Shuttle (STS) solid rocket booster (SRB) at the Morton Thiokol test site near Brigham City, Utah, is currently on hold for lack of time, we feel this project has great potential. Our preliminary investigation showed that the soil has been removed from an area roughly 200m wide and more than 1 km long downrange from the exit cone, providing an excellent picture of the underlying saprolite's geometry; that more than 2m of bedrock has been eroded near the pad, and significant bedrock abrasion occurs at 2m heights in bedrock ledges 1 km downrange (giving an average rate of surface lowering near the pad of 1mm/second of testing!); and that giant ripples (approx. 4m wavelengt'.) form on the fringes of the abraded area, where the soil and gravel from the pad has accumulated.

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8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

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   P. K. Haff

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Brief Outline of Research Findings

During the reporting period January 1, 1988 to June 30, 1988 we have completed a major effort at integrating and unifying the various disparate processes contributing to saltation into a single consistent, quantitative model. Some initial results of this effort were reported in the last semi-annual report, and these have now been drawn together and will be published shortly in Science.

The gist of this accomplishment is as follows. The (assumed steady) wind profile over a fixed surface is modified in the presence of saltation by the drag force imposed by airborne grains. Correspondingly, the force on each grain due to the wind is a function of the total number of grains in saltation. And the number of grains in saltation is, in turn, a function of the impact process whereby grains striking the loose sand bed rebound and eject other grains into the windstream. While these processes were first identified and discussed years ago by Bagnold, it is only now, with the availability of modern computing equipment, that it has become possible to study quantitatively the entire saltating system - wind, airborne grain, and sand-bed - in a unified way. Sand flux, density vs. height profiles, and velocity and ejection angle distributions have been calculated in detail from the model for a monodisperse grain system under a variety of wind conditions. Where experimental evidence is available, mainly in several independent wind tunnel studies of fluxes, and in the careful velocity and angle distribution studies of Willetts and Rice at Aberdeen University, quantitative to semi-quantitative agreement with experiment is obtained.

Some of these results were reported last year. New results include studies of the influence of the strength of the aerodynamic entrainment function on the total mass flux and on the rate of approach to full saltation. It is pleasing to discover that details of the implementation of (still ill-understood) aerodynamic initiation have little effect on the subsequent saltation process.

One important fact about initiation, of course, is the threshold for grain motion. One of the significant results of the unified model is that it exhibits the peculiar hysteretic behavior first detected experimentally by Bagnold, namely that the saltation threshold velocity under increasing wind speeds (the fluid threshold) differs from (is higher than) the threshold found when the friction velocity is decreased during ongoing saltation (the impact threshold). The natural emergence of two thresholds from the model is taken to be strong support for the proposition that the essential physics has been included correctly.

Another peculiar feature of saltation observed experimentally is also reproduced by the model, namely that the mean wind velocity near the ground actually decreases as the wind at height increases. Again this is taken as support that the model is physically correct in its main features.

At the present time we are working to extend the model to polydisperse sand beds, so that a system with realistic distributions of grain diameters can be studied. This will give not only a more accurate model of sand saltation, but, when very small grains are included, will allow a detailed study of the ejection of dust from the bed into the turbulent airstream where it can go into suspension. Initial studies of the impact process when small grains were present in the bed led to non-physical results because the period of the "spring" between contacting grains becomes increasingly small as grain mass decreases, but the integration time step was not reduced sufficiently to accomodate this change. A new set of impact simulations in which this problem is alleviated is under development.

One spin-off from these simulations has been exploratory studies with the so-called lattice-gas model, in which the interaction between grains is simplified dramatically so that a much larger number of particles may be included in the simulations. A proposal to the ARO Short Term Innovative Research Program has resulted in the award of a grant to pursue these ideas.

During the course of the last six months we have benefited from a visit by Brian Willetts and Anne Rice from the University of Aberdeen in Scotland with whose wind tunnel studies of saltation we plan to coordinate our multiple-grain-size simulations under the auspices of a NATO travel grant. Also, we participated in a saltation workshop organized recently at Arizona State University by Ronald Greeley, and we have hopes that eventually some of our "microscopic" simulation work might be coupled with their observations of dunes and dune processes on a large scale.

Our ability to calculate the saltating mass flux given only the wind (shear) velocity and the grain parameters allows us to map out a mass flux law without recourse to empiricism of any sort. We have done this with sand and find the typically observed non-linear behavior of the mass flux law above the threshold. We intend to extend the modeling in two ways: (1) by altering grain quantities (elasticity, size, density, etc.) in order to model the saltation of snow, and (2) by incorporating a variable wind velocity (gustiness). The latter study will lend insight into the reasons behind the typical mismatch between wind-tunnel-based and field-based mass flux data, where presumably the magnitude of the wind velocity fluctuations about the mean are very different.

Simulation of aeolian saltation *

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Results of numerical simulations of single grain impacts into granular beds are condensed into analytic expressions for the number and speeds of grains rebounding or ejected (splashed) from the bed. Coupling of an existing trajectory model [1] with this representation of the impact process, with an expression for the dependence of the number of aerodynamically entrained grains on the fluid shear stress at the bed, and with a feedback involving modification of the wind velocity profile by saltating grains, allows calculation of the evolution of the saltating population and all its characteristic profiles, from inception by pure aerodynamic entrainment through to steady state. Preliminary results reveal realistic behaviour: calculated steady state mass fluxes are within the range of mass fluxes measured in wind tunnel experiments [2-4], and display a similar highly nonlinear dependence on the shear velocity. The role of aerodynamically entrained grains in the system is primarily as a seeding agent; at steady state, splashed and rebounding grains are two to three orders of magnitude more plentiful. The response time of the entire system is roughly one second, or several long-trajectory hop times.

23900-GS

PROGRESS REPORT

TWENTY COPIES REQUIRED

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2. PERIOD COVERED BY REPORT: 1 July 1988 - 31 December 1988

3. TITLE OF PROPOSAL: Saltation & Suspension of Particulate Matter in Air

4. CONTRACT OR GRANT NUMBER: DAAL03-86-K-013[illegible]

5. NAME OF INSTITUTION: California Institute of Technology

6. AUTHORS OF REPORT: Peter K. Haff and Robert S. Anderson

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"Simulation of Eolian Saltation," R.S. Anderson and P. K. Haff, Science 241 (820-823) 1988.

"Eolian Ripples as Examples of Self-Organization in Geomorphbiological Systems", R. S. Anderson, submitted to Earth Science Reviews.

"Computer Simulations of Sand-Surface Self-Organization in Wind-Blown Sand Transport," B. T. Werner submitted to Nature.

"A Steady-State Model of Wind-Blown Sand Transport," B. T. Werner, in press, J. Geology.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

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7/1/88 - 12/31/88

ARO Progress Report

Brief Outline of Research Findings

Our research pace has been somewhat disrupted during the past six months due to major relocations by both the PI, P. K. Haff, and by postdoctoral fellow, R. S. Anderson. Haff moved to Duke University in late September to become Professor of Civil and Environmental Engineering and at about the same time Anderson moved to the University of Santa Cruz where he is Assistant Professor of Earth Sciences.

Because of these moves, we have not yet completed our planned study of simulated saltation with multiple grain sizes. This remains a prime objective for two reasons.

First, we need to determine the sensitivity of the monodisperse saltation models, which we feel are now reasonably well understood, to a loosening of restrictions on the size variation of grains. This is important if we are to have confidence in our estimates of mass transport and other integrated quantities. We have tacitly assumed in our previous published work that it is permissible to use a single mean grain size to represent an "average" bed grain. But the limits of this assumption need testing, as there are clearly cases where it will fail (as in bimodal bed-size distributions where the small grain-size component can "hide" from direct impact in the concavities between large particles).

Second, there are several features of saltation which are inherently grain-size dependent and which require an explicit treatment of the size distribution. Chief among these, for the purposes of the work to be carried out under the remaining terms of this research program, is the generation of dust, via saltation impact on mixed grain size beds.

It may also be possible to generalize from the steady-state type solutions which have been our main focus, to states of either erosion or deposition. Under erosion, for instance, the results of careful splash function studies could be utilized to study armoring of the bed by a lag deposit of larger particles, an effect that could act as a source of significant negative feedback on dust ejection rates.

Another example where mixed grain sizes play an important physical role is in the development of wind ripples, which typically exhibit coarsening grain populations near the ripple crests. Because the dynamics of ripples themselves falls somewhat outside the main thrust of our ARO research program, we have generated a spin-off proposal to the National Science Foundation specifically for the study of ripple form and motion. However, the details of the splash function in polydisperse bed will be a key input to these studies.

We hope to be able to report on developments in these areas in the next program report.

COVER Dune crest in Kelso dunefield, Mojave Desert, California. Foreground ripples illustrate self-organization of fine sand bed into 10-centimeter wavelength ridges oriented perpendicular to wind during saltation. Upper lee face shows grain fall deposition of saltating grains, and subsequent failure as grain flow during later wind event, with wind blowing toward observer. See page 820. [Robert S. Anderson, California Institute of Technology, Pasadena, CA 91125]

Simulation of Eolian Saltation

ROBERT S. ANDERSON* AND PETER K. HAFF

Saltation is important in the transport of sand-sized granular material by wind and in the ejection of dust from the bed both on Earth and on Mars. The evolution of the saltating population and all its characteristic profiles is calculated from inception by pure aerodynamic entrainment through to steady state. Results of numerical simulations of single-grain impacts into granular beds are condensed into analytic expressions for the number and speeds of grains rebounding or ejected (splashed) from the bed. A model is combined with (i) this numerical representation, (ii) an expression for the aerodynamic entrainment rate, and (iii) the modification of the wind velocity profile by saltating grains. Calculated steady state mass fluxes are within the range of mass fluxes measured in wind tunnel experiments; mass flux is nonlinearly dependent on the shear velocity. Aerodynamically entrained grains in the system are primarily seeding agents; at steady state, aerodynamic entrainment is rare. The time for the entire system to reach steady state is roughly 1 second, or several long-trajectory hop times.

SALTATION IS THE PRIMARY MEANS BY which sand-sized particles travel in most realistic winds (*1*). In pure saltation, particles travel smooth paths that are essentially unaffected by turbulent fluctuations of the wind between periodic encounters with the bed; as grain size decreases or wind velocity increases, saltation grades into pure suspension (*2, 3*), where turbulent fluctuations dominate the trajectories. Understanding the physics of blown sand is necessary for accurate prediction of sediment transport on Mars (*4*) and soil loss due to wind erosion (*5*), for understanding the origin of such geomorphic features as ventifacts (*6*) and ripples (*7, 8*), and for reconstruction of environmental conditions from the eolian rock record (*9, 10*). Wind tunnel saltation experiments (*4, 11, 12*) have led to empirical relations between the total mass flux and a characteristic wind velocity, typically chosen to be the shear velocity, u_* (*13*). Profiles of mass flux, $q_m(z)$, and concentration, $c(z)$, decay monotonically and sharply above the bed both in blowing snow (*14*) and in blowing sand (*4, 11, 12*). In addition, natural obstacles have erosion profiles that indicate a distinct maximum in abrasion above the bed (*15, 16*); such profiles constrain the pattern of kinetic-energy flux to the obstacle (*6*).

Earlier workers (*1, 3, 17, 18*) recognized that the initial launch velocities (speed and angle) of grains ejected from the bed are diverse. They used the various profile data to constrain the probability distribution of these velocities. Grain trajectories were integrated forward in time and mass flux and concentration were calculated as each trajectory passed first upward, then downward through a particular height element. Each trajectory and the resulting mass flux and concentration profiles were then weighted according to a chosen probability distribution, the parameters of which were altered until a match was achieved with an appropriate empirically derived profile. Importantly, these matches required a knowledge of the total number of grains in saltation. Typically, the total calculated mass flux was forced to obey an empirically derived relation to the shear velocity (that is, the mass-flux "law") (*3*). In these models the preponderance of grains travel in low-speed, near-bed trajectories; the highest liftoff speeds are the least likely, as observed in nature.

Although the models calibrated for mass flux yielded reasonable concentration and kinetic-energy flux profiles (*6*), they had several severe deficiencies. Reliance on a mass-flux law to set the total number of grains in saltation precluded insight into how the mass flux and the probability distribution of the initial velocities emerged from the physics of the problem. The models were also unable to provide information about the shape of the wind velocity profile. In addition, because nothing was learned about the time scales involved in the approach to steady state saltation (the calibrations were with steady state wind tunnel data), no foundation was laid for the treatment of the more complex case of a variable wind.

Many of the deficiencies of these models can be removed by incorporating the physics of (i) the grain-bed interaction and (ii) the feedback involved in the extraction of momentum from the wind by the accelerating grains (Fig. 1). The grain-bed interaction sets the probability distribution of the initial conditions, and the wind velocity alteration is responsible for eventually limiting the total number of grains in transport. (The energy in the wind is the limiting resource available for the growth of the saltation population.)

We performed numerical simulations of single-grain impacts into a granular bed to evaluate quantitatively the splash process.

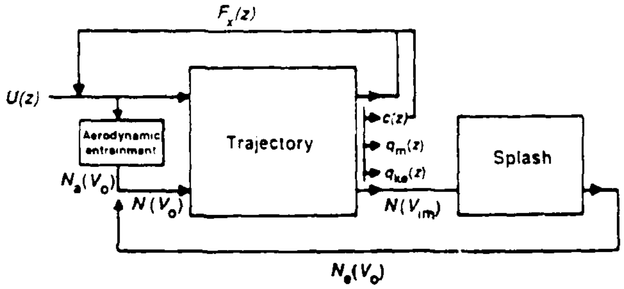

Fig. 1. Schematic diagram of the processes involved in the eolian saltation system. Initial wind velocity profile, $U(z)$, sets aerodynamic entrainment rate, $N_a(V_0)$, in grains per unit area per unit time being ejected from the bed with the lowest possible velocity ($V_{0_{min}}$). Grain trajectories are calculated, resulting in profiles of concentration, $c(z)$, mass flux, $q_m(z)$, kinetic energy flux, $q_{ke}(z)$, and horizontal force on the wind, $F_x(z)$, as well as the impact velocities of each grain trajectory, V_{im}. The grain splash is calculated for each impact according to a probabilistic description (*26*), resulting in a new number of ejecta, $N_e(V_0)$ (including both rebounding and splashed grains), in each of the initial velocity "bins." At each time step the wind velocity profile is modified according to the imposed force profile, resulting in a new shear stress at the bed and a corresponding change in the aerodynamic entrainment rate. The new splash ejecta are added to the new aerodynamically entrained grains to produce the total number of grains leaving the bed at the next step, $N(V_0)$, and the calculation is repeated until a steady state is achieved.

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Eolian ripples as examples of self-organization in geomorphological systems

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Abstract

Anderson, R.S., 1989, Eolian ripples as examples of self-organization in geomorphological systems. Earth-Sci. Rev., xx:xxx-xxx.

Ripples arise spontaneously from sandy beds subjected to winds sufficient to cause the saltation of surficial grains. While the initially fastest growing wavelengths are 4-6 times the mean hop length of grains impelled downwind by long-trajectory high- energy saltating grains, the steady state ripple wavelengths can be several times this. Numerical simulations reveal that a complex process of ripple coalescence is responsible for this evolution of the ripple field. Small, fast-moving ripples catch up with and are absorbed by larger, slower forms, each such merger resulting in a growth of the mean wavelength and a decline in the relative dispersion of the wavelengths. An heuristic argument is presented which accounts for the fast initial growth and subsequent slowing of growth of the mean wavelength as the ripple field evolves. Ripple cross-sectional shape is shown to be controlled in large part by a disentrainment function which represents the declining likelihood of a grain stopping on a surface as it slopes more steeply downwind. That the steady state wavelength in the simulations depends strongly upon impact angle supports Sharp's (1963) suggestion that the length of the shadow zone plays an important role in controlling the final ripple wavelength.

A steady-state model of wind-blown sand transport

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ABSTRACT

A model for steady-state eolian saltation is presented in which a consideration of the interactions between moving sand grains and the wind, and of the collisions between saltating grains and the sand bed are combined to yield results not dependent on experimental measurements of wind-blown sand transport. A steady-state solution is obtained by allowing the feedback arising from the drag forces exerted on saltating grains by the wind and from the saltating grain-bed impacts to operate in an iterative simulation scheme which resembles the time-development of natural saltation. The results provide insight into the feedback mechanism in saltation, into the form of the wind velocity and mass flux profiles, and into a means for separating the saltating and reptating (creeping) grain populations. The numerical solutions give rise to more general arguments in support of the conclusion that fluid entrainment of grains is unimportant in steady-state saltation, and the conclusion that the vertically integrated mass flux dependence on the free-stream friction velocity need not have a simple form.

INTRODUCTION

Eolian saltation is the process by which sand grains are transported in trajectories in a layer close to the surface by the wind. Saltation is recognized as an important geomorphological process for soil erosion and dust storm generation. Sand grains are said to be in saltation when their trajectories are well-determined both by the aerodynamical drag computed from the mean wind profile and by the

Computer Simulation of Sand Surface Self-Organization in Wind-Blown Sand Transport

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Bedforms resembling natural ripples in size and shape appear spontaneously in computer simulations of the evolution of a sand surface under wind-blown sand transport. The wavelength of the simulated ripples does not arise from a dynamical length scale; rather, a quasi-stable wavelength results from the sharply diminishing ability, with increasing ripple size, of statistical fluctuations in surface sand grain transport to promote growth of the wavelength through merger between neighboring ripples.

A loose sand surface over which the wind transports sand grains almost invariably forms quasi-periodic, propagating undulations, eolian (wind-blown) sand ripples, the crests of which are oriented perpendicular to the wind direction (Figure 1). Ripple wavelengths generally lie in the interval $5-20\,cm$ (hundreds of grain diameters),[1,2] and their cross-sectional shape is asymmetical, being steeper on the downwind side. Because of their near ubiquity on sand surfaces subject to eolian transport