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Mechanics of Wind-blown Sand Movements

Springer

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Foreword

Ever since 1930s, human beings have been plagued by disasters caused by desertification and accompanying dust storms. Although basically a result of the evolution of the local inherent environmental conditions, all forms of desertification are also related to the economic development and influenced by global climate changes. Damages caused by desertification not only hinder the economic development, but also aggravate man's living condition. Therefore, the United Nations passed the 3337 General Assembly Resolution on 'Plan of Action to Combat Desertification' in 1975, and desertification has become one of the major concerns of all nations since 1970s. In China, the government has also attached great importance to studies on desertification and ways to control desertification. Since the establishment of the Sand Control Team by Chinese Academy of Sciences (CAS) in 1950's, disciplines involved have been extending from merely physical geography to multi-disciplinary combination of atmospheric science, ecology and mechanics, etc. Nowadays, many scientists and technologists plunge into the multi-disciplinary studies on desertification, they are from various national and provincial research institutions, Universities, and China Meteorological Administration (CMA). In the past 50 years, they have accumulated many experiences on monitoring and controlling of desertification, and also achieved a lot laudability progresses in theoretical researches on desertification.

The physics of wind-blown sand is an issue of basic researches in desertification controlling and sand and dust storm prediction. As early as the 1930s, Bagnold, the British scientist, summarized and classified his field measurements and wind tunnel experiments. In his *The Physics of Blown Sand and Desert Dune* (1941), he established an initial system of wind-blown sand research, laying a foundation in related studies and the engineering application in the controlling of soil wind erosion and desertification. Theoretically speaking, desertification or wind-induced soil erosion is a dynamic process of spatial-temporal evolution manifested by the group behavior of wind-forced sand movement, in which many factors are involved. These factors, to name just a few of them, are the granular characteristic of sand particles, the coupling effect among sand motions, the driving wind field and moving boundary of the landforms, the trans-scale (from micrometer-scale sand particles to centimeter-scale sand ripples, and even to ten-meter sand dunes) characteristics, the nonlinearity (the turbulent characteristics in the near-surface layer, the interaction among wind field, sand motions and thermal effect, and the nonlinearity caused by moving boundary, etc.), and the randomness (the random size distribution of sand particles, the spatial and temporal randomness of wind field, and the stochastic of turbulence, etc.). Due to the extreme complex nature of sand transportation, it remains a most challenging task to scientists, and we still have a long way to go before asserting that we have fully understood its mechanism and rules. Fortunately, achievements in non-linear science and computing technology render further in-depth studies of these complex issues possible with the rapid advancement of science and technology. Moreover, the urgent demand to increase the efficiency of desertification controlling and to vouch for the accuracy of sand (dust) storm monitoring and forecasting also promote studies on the mechanism of wind-blown sand movement in a more quantitative and more profound way.

In the last decade, Professor Xiaojing Zheng, the author of this book, with her team has been working painstakingly on wind-blown sand movement. They started with a basic analysis of its underlying mechanical processes, and then undertook systematical and thorough studies on the formation and evolutional processes of the wind-blown sand flux in the near-surface boundary layer. They have made some remarkable progresses which evolve and renew the extant theories of the physics of wind-blown sand forward to be more reasonable and sophisticated. Based on a summary of the major achievements since Bagnold, the author, in this book, elaborates her with her team's latest researches into the mechanism of wind-blown sand movement. Professor Zheng with her team's main achievements include establishing the kind of statistical method and the stochastic particle-bed collision model to obtain the lift-off velocity distribution function of sand particles, promoting the quantitative investigation on the phenomenon of wind-blown sand electrification and its impact by their experimental measurements and theoretical estimations, realizing the quantitative simulations on the formation and evolution of wind-blown sand flux relating to wind erosion, dust devil, sand ripples and sand dune fields. Furthermore, they formulated some analytical methods and presented experimental results from the mechanical approach, regarding the erecting of straw checkerboard barriers and sand fences, and the formation of soil crust. These remarkable achievements have not only profoundly revealed the underlying dynamic mechanism of wind-blown sand movement but also provided a kind of essential methods for effective design of sand-control engineering, which makes a very significant contribution to the physics of wind-blown sand.

Frequently plagued by raging disastrous sand and dust storms, China vigorously facilitates studies on the controlling of desertification, incubating national projects dedicating to the monitoring, the understanding and forecasting of dust storms. Scientists from CAS, CMA and some universities have made joint efforts to approach related issues from the perspective of atmospheric dynamics, such as the weather system dynamics, climatological statistics, monitoring method and predicting model of dust storms. They have established a comprehensive system, from dust monitoring to predicting, and applied it to operational service.

It is worth mentioning that dust emission scheme is one of the key factors in dust storm forecast and closely related to the fashion of wind-blown sand movement in the near surface layer, which, in turn, is based on the analytic methods and corresponding studies on sand transportation illustrated in this book. Therefore, Professor Zheng's work is also very instructive for investigation on dust storms. In my own research on the dust storm, especially on the dust emission scheme, I have probed into similar issues that Professor Zheng discusses in her work. Professor Zheng and I exchanged ideas on several occasions, and have reached an understanding out of those elaborate talks that both of us are trying to find a solution to an identical problem. Our approaches may differ, but we do share same ideas and benefit from each other's research. We have also been more than once enlightened by Professor Zheng's work.

Last but not least, I have to point out that the complex scientific issues involved in mechanics of wind-blown sand movement, such as multi-scale process, multi-physics field coupling effect, randomness, nonlinearity, and so on, are also paramount concerns shared by scientists working in some other fields. The solution to these problems calls for joint efforts of scientists from different disciplines. Professor Zheng's work is a rewarding attempt to provide answers to some of those questions, and certainly sets, as we have realized, a valuable example for the study of other perplexing dynamical systems, aside from solving these intractable scientific issues in mechanics of wind-blown sand movement.

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Preface

Sand (dust) movement driven by wind force as a natural phenomenon can be seen everywhere in arid desert, farmland, seashore or even broader regions on the earth and other planets including the Mars, Venus, Titan and so on. This kind of aeolian process is usually constituted by three parts including the uplifting from the surface of the earth, atmospheric dispersion, and deposition back to the surface. Whilst wind-blown sand (dust) movement contributes to the formation of the Loess Plateau and the growth of marine fauna and flora, it also causes a series of disasters such as soil nutrient loss, physical damage to farmland, deterioration of air quality, abrasion of engineering facility, etc. These above-mentioned disasters and environmental problems arising from wind-blown sand (dust) movement, to which scholars from many scientific fields other than geographers have paid more and more attention, have always been a governmental as well as a public concern since the 20th century. Despite great achievements have been made in controlling and managing the wind-blown sand hazard in some developed countries, for example, in the United States and Canada, desertification and pollution caused by wind-blown sand movement still remain to be the most serious, most urgent issues in developing countries, especially in China, as the global climate changes.

The transportation of sand (dust) materials by wind force is influenced by a lot of factors: climate, soil type, vegetation cover and soil utilization, to name just a few. Due to its critical dependency, hysteretic nature and high spatial-temporal discontinuity, it is a typical complex natural flow of multi-phases, multi-component media, multi-scale nonlinearity under complex boundaries as well as a comprehensive dynamical system presenting multiple characteristics such as non-linearity, statistical property, diversity, self-similarity, criticality, etc., in which the multi-physics field coupling (wind field, temperature field, wind-blown sand electric field caused by charged sand particles) and multi-processes interaction (atmospheric, ecological, chemical, human activity, and so on) co-exist. Scientific research concerning the transportation of sand (dust) materials by wind force involves issues like multi-scale and multi-field coupling, stochastic and nonlinear process, and complex system, etc., which are also crucial issues confronted by other disciplines. Despite the large amount of progress achieved through long-period field observations, wind-tunnel experiments and theoretical analysis as well as some famous monographs (i.e. Bagnold, 1941; Greeley and Iversen, 1985; Pye and Tsoar, 1990; Shao, 2000; Zeng, et al., 2006, etc.) published, there is still a long way to travel before we arrive at a comprehensive and profound understanding on the mechanism of sand (dust) movement and form a precise prediction of its real physical process; further still, a lot more obligations need to fulfill before we realize an effective simulation and reproduction of the evolution of wind-blown sand flux and aeolian landforms.

Hence, the research approach which combines experiments, modelling and quantitative analysis, as a predominance of mechanics, is probably to the advantage of a deeper understanding of the physical process and basic rules of wind-blown sand environmental problems. Taking this advantage of mechanics into consideration, my team and I have devoted to the research of several typical issues related to aeolian processes during the past decade from a mechanical perspective. Apart from a summary of recent considerable achievements, this book mainly intends to introduce our recent research on the wind-blown sand movement through theoretical modelling, quantitative analysis and computer simulation. The first chapter of this book briefly introduces the situation of desertification and wind-blown sand disasters in China, especially North-western China. Chapter 2 summarizes the characteristics of the wind field in the atmospheric boundary layer with a particular emphasis on the turbulent property of the wind field. Chapter 3 devotes to the introduction of researches on sand's lifting off the sand bed surface, including the linear and angular velocity of sand particles lifting from the bed, their distribution and the representation of the particle-bed collision process. Chapter 4 is a description of the wind-blown sand electrification and its effect on sand saltation movement. Chapter 5 is dedicated to an analysis of the forces on sand particles and their trajectories, and is also an introduction to the experiment and theoretical prediction of sand transport rate, and in particular, the electric and thermal effect on the development of wind-blown sand flux, as well as the prediction of sand movement and transport intensity under a fluctuating wind field. Chapter 6 and 7 are devoted to the introduction of the formation and evolution of some typical aeolian landforms like ripples and dunes. Chapter 8 presents the mechanical analysis method to estimate the efficiency of sand prevention methods.

This book aims at serving as a reference for researchers and graduate students who major in geo-related sciences, such as physics of wind-blown sand, environmental science, geophysics, atmospheric science, etc., mechanics as well as applied mathematics, broadening the readers' horizon on the latest development of the quantitative research on wind-blown sand movement and enhancing their competence to apply basic methods in this field. What I strive for is provide some methods and principles which may be helpful to researchers interested in the wind-blown sand movement and other environmental issues via this book, which, on one hand, may help researchers and students of geology and atmospheric science understand what can be absorbed from mechanics to push investigations on wind-blown sand movements in a more rational and quantitative manner and on the other hand, provide researchers and students expertise in mechanics, mathematics, physics and environment-related engineering with a smooth access to the research field of wind-blown sand movement. In this case, both parties mentioned above can unit their efforts to promote an understanding of the mechanism of wind-blown sand (dust) movements and push forward the development of this interdisciplinary research. By the way, with the publication of this book, I would also hope that more and more scholars and experts in the world will pay their attention, further their professional suggestions and actions to aeolian environmental problems in China.

Since the first day I set foot in the field of wind-blown sand movements, I have been inspired by some scholars in Geosciences and atmospheric sciences as follow: Prof. D. A. Gillette of National Oceanic and Atmospheric Administration (USA), Prof. Y. P. Shao of the Institute of Geophysics and Meteorology, University of Cologne, Academician H. L. Sun and D. H. Qin, Dr. P. Cui, Dr. Z. H. Lin, Dr. T. Wang, Dr. J. J. Qu, Dr. Y. Q. Ling, Dr. Z. B. Dong of Chinese Academy of Sciences (CAS) and Academician Y. T. Chen of China Earthquake Administration as well as Dr. X. Y. Zou of Beijing Normal University. Besides, some scholars in Mechanics like Prof. K. Moffat, ex-President of the International Union of Theoretical and Applied Mechanics (IUTAM, 2000-2004), Prof. F. Hussain (Member of the National Academy of Engineering and the Academy of Sciences for the Developing World) of the University of Houston, and several ex-Presidents of the Chinese Society of Theoretical and Applied Mechanics (CSTAM), including Academician Z. M. Zheng, Y. L. Bai, and E. J. Cui, etc., also offered me very important assistance. I would like to take the opportunity to express my gratitude to them. In particular, I would like to appreciate Academician H. Zhou of Tianjin University, Academician Q. C. Zeng of the Institute of Atmospheric Physics, CAS, and Academician J. C. Li, President of CSTAM, who not only provided much important and detailed guidance, but also paid much attention to my research work. All these concern and encouragement have been urging me keep going forward.

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Contents

Symbols

In this text, hundreds of different physical quantities are included in various formulations. Use of the same letters or symbols for different concepts has been unavoidable. Choice of notation was affected by the desire to retain commonly used notations familiar in each field of study, while at the same time avoiding ambiguity by making a single choice where two or more symbols for the same quantity are known to exist in the literature.

Main symbols commonly used in this text are listed below, unless otherwise defined in the text, the meaning of symbols, are understood:

x,y,z	Cartesian coordinates
$\mathbf{u}(u,v,w)$	velocity vector of fluid (velocity component in coordinates x,y,z)
x_i	ith coordinate (i = 1, 2, 3)
$\mathbf{e}$	the unit vector of the coordinates with $\mathbf{e_i}$ in the direction of x_i
μ	viscosity of fluid
μ_t	turbulent viscosity or eddy viscosity coefficient
ν	kinetic viscous of fluid
Re	Reynolds number
ρ	density
ν	kinetic viscous of fluid
U	characteristic velocity of fluid or velocity
L	length
H	height
P	thermodynamics pressure
T	temperature
$\mathbf{f}$	body force vector
$\mathbf{T}$	surface force tensor
q_T	heat flux
S_T	viscous dissipation term
λ_T	thermal conductivity
γ_d	atmospheric dry adiabatic lapse rate
k_T	thermal diffusivity
e	internal energy
c_p	heat capacity at constant pressure of fluid phase
g	gravity acceleration
R	Molar gas constant
t	time
Δt	time interval
l_m	Prandtl mixing length
k	Karman constant
σ_k	Prandtl number of the turbulent fluctuation momentum
ε	turbulent dissipation rate
c	concentration of solid phase in two phase flow
P^0,ρ_0,T^0	pressure, density and temperature of static atmosphere

p,ρ',T^d	variation of thermodynamic quantities caused by flow	N_s	number flux of saltation particle from surface bed
		N_a	number flux of particles entrained directly by the aerodynamic force of air flow
u_{*t}	threshold friction velocity for bare-sand(soil) surface		
u_{*0}	surface friction velocity	σ	standard deviation or basal-to-frontal area ratio of vegetation
u_*	friction velocity of fluid		
		S_k	skewness
$(u_{*t})_V$	threshold friction velocity for vegetated surface	K_x	kurtosis
		I	turbulence
		T_g	wind gusts period
u_t	threshold fluid velocity at height z	D	particle diameter
		ρ_s	density of sand particle
u_{*a}	friction velocity of wind in saltation layer in wind-blown sand	D_s	diameter of sand particle
		m_s	mass of sand particle
z_0	aerodynamic roughness length	V_s	volume of sand particle
z_s	equivalent roughness or movable bed roughness in wind blown sand	$\mathbf{V}_s$ $\dot{x},\dot{y},\dot{z}$	resultant velocity vector of sand particle (velocity component in coordinates x,y,z)
τ_0	shear stress at the upper boundary of the saltation layer in wind-blown sand	θ	angle of sand velocity to the horizontal or potential temperature
		η	porosity of the sand bed or fence
τ_a	shear stress in the satation layer	E	kinetic energy of moving particle or Young's modulus of crust
τ_c	critical fluid shear stress		
τ_s	vertical momentum flux produced by sand movement	α_{dune}	velocity acceleration factor on the dune
H_s	thickness of mean saltation	u_{*crest}	friction velocity on dune top

$u_{*-\infty}$	friction velocity of the inflow far away from dune
$\mathbf{F}_D$	aerodynamic drag force
$\mathbf{F}_g$	gravity force
$\mathbf{F}_L$	aerodynamic lift force
$\mathbf{F}_M$	Magnus force
$\mathbf{F}_E$	electric force
$\mathbf{F}_s$	Saffman force
$\mathbf{F}_B$	Basset force
$\mathbf{F}_\mathrm{i}$	inter-particle force
$\mathbf{F}_{pn}$	normal contact force in the process of particle colliding
$\mathbf{F}_{f\tau}$	tangential friction force in the process of particle colliding
$\mathbf{F}_{rn}$,$\mathbf{F}_{r\tau}$	normal and tangential damping forces in the process of particle colliding
$\mathbf{F}_x$	force acting on the wind per volume resulted from sand transport
C_D	aerodynamic drag coefficient
C_L	aerodynamic lift coefficient
λ_V	roughness density, frontal area index of vegetation roughness
σ_V	basal-to-frontal area ratio of roughness element or vegetation
χ	angle between the wind direction and the normal line of the bed surface
α	surface slope angle
β,α_k	impact and contact angle of sand in the process of impact with bed surface
ω	spin angular velocity
N_r, N_e	numbers of rebound and ejected sand particles
V_{im}	Impact velocity of sand particle
$\overline{N}_{ej}$	mean number of sand particles jumping from the bed per impact
V_r, V_e	rebound velocity and ejected velocity of sand particle from bed, respectively
V V_x, V_y, V_z	resultant lift-off velocity of sand particle from bed
$\mathbf{E}_\mathrm{s}$ E_x,E_y,E_z	wind sand electric field vector
E_a	atmospheric electric field
E_{a0}	atmosphere electric field at ground level
δ_e	density of surface charges at ground level
ε_0	electrical permittivity of air
ε_s	permittivity of sand particle
C_q	charge-to-mass ratio of charged sand particle
q^c	particle charge

ρ_q	volume charge density	RSI	ripple symmetry index
σ_q	surface charge density	RI	ripple index
E_{sz}^1, E_{sz}^2	electric field produced by saltating and suspending particle, respectively	λ	wavelength of sand ripple
		α_{ss}, α_{ls}	stoss and lee slope angle of sand ripple
E_{cz}	electric field produced by sand particles in sand bed	V_d	migration velocity of sand dune
E_i	electric field of incident electromagnetic wave penetrating in the spherical sand particle	H_{supply}	thickness of sand supply
		h_{tun}	height of wind tunnel
		u_{ax}	axial wind velocity of wind tunnel
σ_w	vertical velocity standard deviation of air parcel	h_0	straw height of straw checkerboard barrier
w_{st}	terminal settling velocity of sand particle	$l_{\max}$	maximum distance of two adjacent straw grids of straw checkerboard barrier
P_{sal}	saltation parameter		
σ_w^s	vertical velocity standard deviation of sand particle	w_e	elastic deflection of crust because of saltation impact
τ_L	Lagrangian time scale of air parcel	$W(t)$	creep deflection function of crust
T_L^*	modified Lagrangian time scale of air parcel along the sand particle trajectory	$p(\cdot)$	collision probability of saltating particle
		$f(\cdot)$	distribution function
I_s	processional moment of sand particle	Q	sand transport rate
		q	mass flux of sand

Subscripts

ij tensor
s sand
f fluid

Unsuperscripted or Superscripts

$(\bar{\ })$ mean of the physical quantity
$(\ ')$ fluctuation of the physical quantity
$(\dot{\ })$ time rate
$(\ddot{\ })$ second derivative with respect to time