实验风沙物理与风沙工程学

刘贤万 著

科学出版社

中国科学院科学出版基金资助出版

实验风沙物理与风沙工程学

刘贤万　著

科学出版社

1995

（京）新登字 092 号

内 容 简 介

本书是作者长期从事风沙物理与风沙工程实验研究的成果总结，也是风沙科学与力学相结合的最新尝试，它是目前国内外一本较为全面论述风沙科学问题的专著。全书包括风沙概论、沙粒运动力学、风沙气固两相流体动力学、风成床面形态的运动和风沙工程五大部分。内容丰富，资料翔实，并附有大量图表和实验照片。

本书适合风沙地貌、风沙运动力学、风沙灾害、风沙工程和沙漠化防治的科技工作者，以及国防、交通、林业、土壤、水土保持等方面的工程人员和高等院校有关师生参考。

实验风沙物理与风沙工程学
刘贤万 著
责任编辑 吴三保
科学出版社出版
北京东黄城根北街 16 号
邮政编码：100717
激光照排 新华公司
北京市顺义县顺达印刷厂印刷
新华书店北京发行所发行 各地新华书店经售
*
1995 年 8 月第 一 版 开本：787×1092 1/16
1995 年 8 月第一次印刷 印张：14 1/4 插页：25
印数：1—550 字数：332 000
ISBN 7-03-004681-1/P・833
定价： 29.50 元

序　言

沙漠学是在传统的地学、生物学和数理等学科的基础上发展起来的一门新兴边缘学科。它以占地球陆地面积约 1/3 的干旱、半干旱、甚至部分半湿润地区的沙漠、戈壁及风沙化土地等客体为研究对象。人们把这一由岩石圈、生物圈、水圈、大气圈及人类社会圈的多相界面及其交互作用构成的特殊陆地景观及生态系统作为相对独立的整体，研究其中物质、能量转换机制，资源、环境构成及其与人类社会的关系，以寻求其协调与持续发展的途径。总之，沙漠学是融空间科学、环境科学、资源科学为一有机整体，由地球科学、生物科学、人文科学、数理科学，以及经济、技术等科学交叉、渗透而发展起来的一门学科。从目前学科发展水平来看，沙漠学有三大分支：沙漠资源学；沙漠环境与灾害学；沙漠地区社会经济学。

实验风沙物理与风沙工程学是沙漠学的重要组成部分，是一门重要的应用基础学科。它是通过室内风洞实验与野外实验观测相结合，理论分析与实验模拟相结合，以及把传统的地学、风沙地貌学等与数力科学相结合的一个最新尝试。它主要研究风沙问题的内含（实质）、沙颗粒运动、风沙气固两相流体动力学、风沙地貌学和风沙工程学等课题，同时努力对风沙实验相似理论进行有益的探讨。因此，本书是继 R. A. 拜格诺《风沙和荒漠沙丘物理学》经典著作问世以来，又一部最新的风沙科学研究成果。

本书在如下问题上取得了进展：

(1) 通过室内风洞和野外条件下进行的沙粒运动动态摄影，首次明确地提出了沙粒运动可分为 5 个主要运动阶段或主要运动形式。书中清晰地描述了其运动物理图象，并通过受力分析，建立了自己的力学模型及相应的数学关系式。

(2) 把风沙运动提高到多相流体动力学高度来进行研究。通过对一般多相流体动力学方程组的简化，建立了风沙气固两相流体运动的数力模型，并求其解析解。

(3) 对沙纹和风沙工程进行力学分类，并提出沙纹的沉积波形成说和引入风沙工程的力学基本模型——边界层里的平板平面绕流模型。

(4) 把二次流的概念引进沙丘生命史的研究中。

(5) 提出一套较为系统的风沙实验相似准则。

总之，本书以作者他们自己的实验和观测材料为主，并广泛吸收国内外相关成果，把风沙这一地球科学问题与数力科学结合起来，对风沙科学的一系列重要的问题，作了较系统、深入的研究，从而将风沙物理与风沙工程学的初步轮廓展现在我们面前。

作为一本风沙科学专著，对于地表风蚀、风沙流运动、沙尘吹扬及沉积，应有较全面的阐述，但本著作对沙尘暴及沙漠化等重大自然灾害，尚未专门论及。关于风沙工程方面，对化学、生物等防治措施也涉猎不够。同时，在研究方法上，除研究共性问题外，还应对各种工程的个性问题有所论述，这样，才能达到发挥综合防护体系的最大效益，发挥其环境保护的作用。

纵观全局，本书作为一部应用基础理论研究专著，是具有较高的理论学术水平和实践应用价值的。作为一位老沙漠科学研究工作者，对科学的每一点进步都倍感欣慰和兴奋，于是写下上述一点文字，是以为序。

夏训诚

1994 年 6 月 11 日

PREFACE

Eremology is a new frontier science germinated the basis of the traditional earth science, soil science and biology etc. Its main research objects are sandy desert, gobi and other aeolian sand lands in arid, semiarid and subhumid zones which cover more than one-third of the earth's land surface. People often view such special terrestrial landscapes and ecosystems as a relative independent realm formed at the multiphase interface among lithosphere, biosphere, hydrosphere, aerosphere and sociosphere to study the transport mechanisms of material and energy, the constitution of resources and environment and their relations with human society so as to seek a harmonious and sustainable development way. In short, eremology has been developed through the inter-exchange and inter-infiltration of multi-disciplines, such as space science, environment science, resource science, earth science, biology, humane studies, mathematics, economy and technology etc. Viewed from the present development status, the eremology can be divided into three major branches: desert resource; desert environment and disaster; and desert socio-economics.

Experimental wind-sand flow physics and sand drift control engineering, as a foundation of applied research of the last two branch sciences, is an important component of the eremology. It makes the traditional earth science, aeolian sand geomorphology, mathematics and physics combine with each other through indoor wind tunnel experiments, field observations, simulation trials and theoretical analysis. It mainly studies the nature of sand drift problem, sand grain movement, dynamics of two-phase gas-solid flow of wind and sand , aeolian sand landforms, sand drift control engineering and similarity theories on wind-sand flow experiments etc. Therefore, it may be said that this book represents a new achievement in the blown sand research field since R. A. Bagnold published his classic work *Physics of Blown Sand and Desert Dunes.*

This book has made some progress in the following respects:

1. Based on sand grain dynamical photography taken in indoor wind tunnel and field conditions the auther put forward that sand grain movement can be divided into five stages of forms. Their physical images and the forces acting on the grains were analysed and their mechanical models as well as mathematic expressions were established.

2. Sand movement by wind was studied from a multiphase hydrodynamic angle and the mathematical model of two-phase gas-solid fluid movement was establised through simplifying and solving the general multiphase hydrodynamic equations.

3. Both the sand ripples and sand drift control engineering were classified from a mechanical angle, thus put forward a conception of depositional wave formation of sand ripples and used it in the basic mechanical model of sand drift control engineering, namely boundary-layer flat-plate plane flow model.

4. The secondary flow conception was introduced in the study of life history of sand dunes.

5. A complete set of similarity criterion for wind-sand flow experiments was developed.

Based on the author's experiment and observation data as well as widely consulting others' research findings this book makes blown sand problem in the earth science field combine with mathematics and physics; systematically elucidates some important problems in blown sand sciences and unfolds a profile of wind-sand flow physics and sand drift control engineering before our eyes.

As a eremologic monograph, this book comprehensively describes ground surface deflation, sand movement by wind and dust entrainment and settlement but few data are available in sand-dust storm disasters, this is no doubt a problem to be solved in the future, in addition the chemical and biological sand drift control methods are not fully described. To achieve better sand drift control results for our econmy and environment improvement, we need detailly understanding eremology both in the general character and individulity. Even so, this book remain a valuable research achivement of the applied fundamental theory, with a high academic level and practical value.

As a desert reseach scientist, I am always pleased to see any progress my colleagues have made and hence I wrot this preface for this book (translated by Cheng Daoyuan).

Xia Xuncheng
11, June 1994

前　言

风沙指的是运动的空气——风，对干燥疏松的沙土颗粒地表进行侵蚀——风蚀，而产生的气固两相流体。因而，风沙物理学与风沙工程学就是以物理力学的观点来研究风沙运动、风沙动力学过程、风沙地貌和风沙危害的形成、发展及防治原理和防治工程设计原则等的一门应用基础理论学科。风沙两相流体动力学是多相流体及气固两相流体动力学的一个重要组成部分和分支学科。经典的多相流体动力学是把颗粒相看作拟流体那样具有连续介质特性的流体。因此，对于具有复杂形状、很宽粒配和一定的水平及垂直浓度变化的地球边界层中的风沙流体动力学过程，是具有很大特殊性的。而风沙工程的理论模型是边界层上气固两相流体的平板绕流，它比理想流体及粘性流体在均匀场中的平板绕流更加复杂和多变。因为固体颗粒在绕流过程中会产生沉积，并且反过来影响绕流运动本身。总之，我们的风沙物理与风沙工程学研究的是风沙科学中的一些基本问题，应用的方法则是把地学与数学力学结合起来，继承已有的科学成果，以期解决风沙科学及工程防治中的一系列基本课题。

风沙物理学的系统深入研究，可以认为是从把现代空气动力学实验设备——风洞，引入风沙科学实验后开始的。因此，我们把英国物理学家拜格诺（Bagnold，R. A）于1941年出版的《风沙和荒漠沙丘物理学》及原苏联学者兹纳门斯基（Знаменский，А. И.）于1958年出版的《沙地风蚀过程的实验研究和沙堆防止问题》等专著列为经典著作。把伊万诺夫（Иванов，А. П.，1972）著的《沙漠风蚀的物理原理》、巴兹等（Baz，F. E. et al.，1986）主编的《沙漠化物理学》（Physics of Desertification）和丹麦奥尔胡斯大学主编的《国际风沙物理学术会议论文集》三卷本（1985）等视为后续佳作。而风沙工程学的研究，特别是应用风沙工程来进行治沙和防止土壤风蚀的工作，实际上可以追溯到十分久远的人类历史时期。今天，一些工程治理风沙危害的著作已陆续问世，如《土壤风蚀及其防止》（雅柯波夫，Т. Ф.，1956）、《铁路防沙》（彼得普梁多夫，Н. А.，1958）、《沙漠地区公路工程》（吴正等，1981）和《土壤侵蚀》（柯比克，M. J.，1987），等等。但总的看来，风沙物理学与风沙工程学还处在其发展的初期，距成熟还有一段艰难的路程。

当前，国际上许多有识之士已经认识到：环境退化和土地沙漠化，已经不是一个地区、一个国家的问题，而是全球性的重大问题。地球实在太小了。世界沙漠化发展与地球环境问题，越来越多地引起各国的重视。一个国际合作控制世界土地沙漠化和地球环境退化的热潮正在到来。自1977年联合国在内罗毕举行第一次国际沙漠化大会以来，世界性的相关学术活动明显增加。其中，在风沙物理和沙漠化物理学方面的学术会议就有：1980年联合国教科文组织和国际理论物理中心分别在意大利那不勒斯和的里雅斯特召开的沙漠化物理学讨论会；1985年由丹麦奥尔胡斯大学主持召开的风沙物理学学术会议；1991年为纪念风沙物理学奠基人R.A. 拜格诺而专门举行的风营力机制学术会议。

上述国际会议集中讨论的是沙粒运动、土壤风蚀、风成基面形态运动、沙尘暴、沙漠化形成机制、风沙危害防治和空间时代新技术应用及风洞、野外试验研究等课题。至于风沙物理学或沙漠化物理学的发展前沿，从的里雅斯特会议的主持者之一——哈桑（Hassan，M. H. A.，1985）的看法中可见一斑。

（1）利用风洞实验综合研究和理论分析，以理解近地表沙粒的三种运动：蠕移、跳跃和悬浮；

（2）详细研究了解各种沉积波纹和沙丘（纵向、横向、新月形和星形）的运动和形成；

（3）利用各种风洞实验和现代仪器，以及理论分析，精确确定造成尘埃产生、迁移和沉积的气象和土壤因素；

（4）进一步研究和发展土壤风蚀方程，以确定产生风蚀的主要影响因素。

众所周知，沙漠化是当前世界上面临的一个严重的环境问题。全世界每年平均有（5—7）$\times 10^4 km^2$土地沦为沙漠化土地，有近 100 个国家和地区、8.5 亿人口受到沙漠化的威胁。在我国，沙漠化土地也以平均每年扩大 2 370km^2 的速度发展。

沙漠化，归根结底是一个风蚀问题。而为了制订防治土地沙漠化的有效措施，就需要有阐明风沙运动和风成地貌形态的形成、发育规律，以及防治风沙的风沙物理学与风沙工程学的理论与方法作为指导。

中国科学院兰州沙漠研究所在已故中国科学院竺可桢副院长和钱学森教授的关怀和支持下，于 1967 年建成了我国第一个风沙环境风洞实验室，并全面开展了野外风沙运动和防沙（及防风吹雪）工程的模拟实验研究。自 1985 年以来，我们结合基金课题——风沙物理与风沙工程的研究，系统地进行了有关土壤风蚀、风沙运动、风成地貌的形成演变，以及多种防沙工程措施的野外试验和室内风洞模拟实验研究。本书正是上述研究成果的归纳和总结，同时也参考了国内外同行的有关研究文献资料。书中力图运用物理和数力学的基本原理进行分析，阐明风沙运动和风成地貌发育的机理，以及风沙工程的作用原理。通过这一研究，希望开辟一条新的风沙运动与风沙工程研究的道路。

本书在具体内容设置上，首先指出风沙问题的内涵和实质（第一章），然后由单一颗粒运动研究（第二章）到风沙气固两相流体动力学初探（第三章）和风成基面形态运动求源（第四章），最后简述风沙危害的工程防治问题（第五章）。在每章的行文中，先由引言导出问题，指出范围，然后由点到面、由个别到一般地对实验结果进行分析、讨论，最后以野外实验观测资料加以验证，以求对所述问题有个较完整的概念。

值此书稿付梓之际，自知十年一果，难列仙桃，但回顾基金研究课题完成和成书历程，却是百感交集。不少难事、快事，历历在目，回忆起来，倍觉亲切。1985 年申请基金的时候，朱震达所长、邹本功（已故）室主任和凌裕泉先生，给予极大的支持，并成为申请小组的合作成员。他们从选向到定题，从研究提纲到实施细则，都给予具体的指导和协助。而风洞实验室的同志们，则为计划的具体执行，付出了巨大的精力和前后数载的辛劳。李长治高级工程师在风洞实验中付出的精力最多，为了一组数据的精确，曾反复实验，精心求索；王国昌和刘玉璋两位工程师，不仅参加许多室内实验，而且在各次野外实验观测中进行了艰苦和创造性的工作；杨佐涛和吴丹两位实验师，不仅参加了室内实验和各次野外试验观测工作，而且还负责了许多实验资料、特别是高速摄影资料的判读和整理工作。总之，没有风洞实验室全体同志认真、艰苦的协同工作，就没有本基金课题的胜利完成，更没有本书终于问世的今天。

在这里特别要提到的是我们的原室主任、现任教于华南师范大学地理系的吴正教授，他在教学、科研的百忙之中，花费了大量宝贵的时间和精力，为本书的初稿全文进行了逐字逐句的批改和审阅，直至对打印送审的第二稿，又进行逐章逐节的批阅，提出了许多进一步修改的意见。由此我们可以看到一位终生不离风沙科学前沿的风沙地貌学家，是怎样关怀后来者的成长和关心风沙科学的每一点成绩及每一点进步的。吴正教授的拳拳之忱，令人没齿不忘。还有钱宁教授（已故）、郭秉荣教授、刘振生研究员和我中国科技大学的老师顾震潮（已故）和周秀骥院士、童秉刚和徐延侯老师，他们都曾对本基金课题的不同研究阶段及部分论文初稿给予指导和提出了宝贵的修改意见。此外，本基金课题和本书的完成，也与顾佩多年的支持、帮助和照顾分不开的，她为本书的全部图件进行了数次精心的修改、清绘，为本书的出版增色不少。借此机会作者谨向各位师长和同志们，一并致以衷心的感谢。

最后，应该声明的是，本研究课题是在国家（原先是中国科学院）自然科学基金资助下得以完成的，而本书的出版，又是在中国科学院科学出版基金和兰州沙漠研究所所长基金的资助下得以问世的。作者在此谨向国家自然科学基金委员会、中国科学院科学出版基金委员会和中国科学院兰州沙漠研究所所长致以崇高的敬意。

福建泉州　刘贤万

1994 年 4 月于兰州

INTRODUCTION

Wind-sand flow refers to the two-phase gas-solid fluid caused by moving air-wind, which acts on soil particles on dry and loose ground surface and sets them in motion deflation. Wind-sand flow physics and sand drift control engineering as an applies fundamental science studies such problems as the blown sand movement, dynamics of blown sand, aeolian sand landforms, the formation of sand drift disasters, their control theories and engineering design principles from the physical viewpoint. The dynamics of two-phase wind-sand fluid is an important component or branch of multiphase fluid and two-phase gas-solid fluid dynamics. Classical multi-phase fluid dynamics can be regarded particles-gas phase as a pseudo-fluid with continuous medium property. As for the dynamical process of the wind-sand fluid in the earth boundary layer, it has complex shapes, very wide particle grading as well as horizontal and vertical concentration variations, therefore it has a considerable particularity. The theoretical model of the sand drift control engineering falls into the flat-plate flow of the two-phase gas-solid fluid in the boundary layer and hence it has much more complex and variable properties than the flat-plate vortex flow in the conditions of ideal fluid or viscous fluid in the even field. Because solid particles can be settled out during the flowing processes and in turn affect the particle flow itself. In short, wind-sand flow physics and sand drift control engineering studies some basic problems in eremology by means of the combining method of earth science, mathematics and mechanics and relevant knowledge which our pioneers had found in eremology so as to solve some essential problems on the blown sand and sand drift control engineering.

It is generally accepted that the systematical and in-depth study of the physics of blown sand began with the introduction of modern aerodynamical experiment equipment-wind tunnel into the blown sand scientific experiments. Although the classical works such as *The Physics of Blown Sand and Desert Dunes* By British Physicist R. A. Bagnold published in 1941 and *The Experimental Study on Wind Erosion Process of Sany Land and Sand Drift Control* by former Soviet Union scholar, A. E. Znamenskii published in 1958, and later distinguished works like *The Physical Principles of Desert Wind Erosion* by A. P. Evanrov published in 1972 as well as *Physics of Desertification* by F. E. Baz published in 1986, the history of the studies on sand drift control engineering, especially the sand dune stabilization and soil wind erosion control activites, can be traced back to ancient times. Nowadays there were some works on sand drift control engineering come out in succession, such as *Soil Wind Erosion and Prevention* by Yakobov, T. F. (1956), *Prevention of Sand Damage to Railway* by Petpniandov, N. A. (1958), *Highway Engineering in Desert Land* by Wu Zheng et al. (1981) and *Erosion of Soil* by Kobek, M. J. (1987). However, as a whole, the studies on the blown sand physics and sand drift control engineering are still in the initial development stage, it still has a long way to go to reach the mature.

At present, people have recognized that the environmental degradation and land desertification are by no means a regional or a country's prolblem, instead they are a global issue. The land resources on our earth are not sufficient. These problems have attracted widespread international attention. A worldwide cooperative activity for combating desertification and environmental degradation is putting into action. Since the United Nations Conference on Desertification held in Nairobi in 1977, the international academic activities on this subject have increased markedly, for instances, the International Workshops on the Physics of the Desertification, sponsored by UNESCO and the International Centre for Theoretical Physics in Neapoles and Trieste, Italy in 1980; The Symposium on the Physics of Blown Sand Sponsored by the Aarhus University, Denmark in 1985; and the International Symposium on the Mechanism of Wind Stress held in 1991 in memory of R. A. Bagnold. The above-mentioned international conferences dealt with a wide range of topics, including the mechanism of sand grain movement, soil wind erosion, aeolian bedform process, dust storm, land desertification, sand drift control, wind tunnel experiment, field experiment and the application of space-age new techniques etc.

So far as the present development frontiers of the physics of blown sand and land desertification are concerned, M. H. A. Hassan, one of chairmen in Trieste Symposium , mentioned the following several respects.

(1) Through wind tunnel experiments and theoretical analysis to understand three forms of sand grain movement in near-surface layer, including saltation, creep and suspension.

(2) The fromation causes and the movement of deposition ripples and sand dunes (including longitudinal dune, transverse dune, crescent dune and star dune).

(3) Through wind tunnel experiments, modern instrument determinations and theoretical analysis to understand precisely the meteorological and soil factors responsible for the formation, transport and settlement of dust particas.

(4) Further study on the soil wind erosion equation is required to determine the main factors affecting soil wind erosion.

As is well known to us, desertification is one of the most serious problems facing the world today. Every year about 50,000—70,000km^2 of lands are reduced to desertified land in the world, affecting the livelihood of 850 million people in about one hundred countries. In China, the desertification is expanding at a rate of 2,370km^2 per year.

The land desertification is mainly manifested in soil wind erosion. To be able to formulate some effective measures to cope with this problem, we must have a better understanding to the formation and development laws of wind-sand activities and aeolian sand landforms as well as the blown sand physics and the principles of sand drift control engineering.

The Lanzhou Institute of Desert Research, Chinese Academy of Sciences, with the great support of the academy's late vice president, Zhu Kezhen and professor Qian Xuesen et al. set up Chian's first laboratory of experiment wind tunnel about wind-sand environment in 1967. Since then a series of simulation experiments on sand drift and snow drift control engineering have been conducted. From 1985 onwards, scientiests of the institute in our research subject "study on wind-sand flow physics and sand drift control engineering" which was supported by the national foundation conducted systematical wind tunnel simulation experiments and field observations on soil wind erosion, wind-sand movement, formation and evolution of aeolian landforms and sand-drift control measures etc. This book is actually a generalization and summation of above-mentioned experiments and research works. Much relevant data which we obtained both from home or abroad were also very helptul in our works. In this book the author tried to use the basic principles of physics and mathematics to analyse and elucidate the mechanisms of blown sand movement and the formation of eolian landforms as well as the principles of sand drift control engineering. It is hoped that this will contribute to open a new way for the studies of blown sand movement and sand drift control engineering.

This book consists of five chapters. Chapter 1 elucidates the connotation and the nature of sand drift problems; Chapter 2—3 discuss the dynamics of single particle movement and the two-phase gas-solid fluid; Chapter 4 describes the movement of aeolian bedforms; and Chapter 5 outlines the engineering control problems of sand drift hazards. Each chapter begins with an introduction, then from isolated points to a whole area to point out the concerned problems and the analytical results of relevant experiments, thus we can get an overall idea about the deseribed problems.

The book will soon be sent to press, at this moment. I recall ten years search in sand and dust. Many joys and sorrows return before my eyes. The publication of this book would not have been possible without the help of many people. I am grateful to professor Zhu Zhenda, the ex director of the Institute of Desert Research; Professor Zou Bengong (late) and professor Lin Yuquan, who directed and helped me to select this research subjuct and obtain the fund support from the National Natural Science Foundation in 1985. I would also like to thank Li Changzhi, senior engineer; Wang Guochang and Liu Yuzhang, engineers; Yang Zuotao and Wu Dan, technicians, for their prolonged industriousness in making wind tunnel experiments and field observations and obtaining a wide range of valuable data.

I am deeply indebted to professor Wu Zhen, ex-director of the wind tunne laboratory and present profesor of the South Chian Teachers College, who took time off his busy schedule and gave a detailed revision to the final manuscript. Thanks are also due to professors Qian Ning (late), Guo Bingrong, Liu Zhenshen; my university's (Univ. of Science and Technology of China) teacher Gu Zhenchao (late), Zhou Xiuji, academician of the Chinese Academy of Sciences, and Xu Yanhou, who made some helpful comments on parts of the draft of the book. I am also very grateful to my wife Mrs. Gu Pei for her continued patience in drawing part of figures and revising the final proof of the book, making it much better than it would otherwise have been.

Finally, I would like to thank the National Natural Science Foundation and the Publication Commission of the Chinese Academy of Sciences and the director of the Lanzhou Institute of Desert Research for funding the subject and the preparation of this book.

Quanzhou, Fujan LIU XIANWAN
Institute of Desert Research, Chinese Academy of Sciences
Lanzhou, China. April 1994.

目　录

序　言……………………………………………………………………………（ i ）
前　言……………………………………………………………………………（ v ）
第一章　风沙问题……………………………………………………………（ 1 ）
引言……………………………………………………………………………（ 1 ）
第一节　风蚀……………………………………………………………………（ 1 ）
一、风蚀的危害…………………………………………………………………（ 1 ）
二、风蚀研究的进展……………………………………………………………（ 2 ）
三、土壤风蚀原理………………………………………………………………（ 3 ）
第二节　磨蚀……………………………………………………………………（ 11 ）
一、物体的外打磨………………………………………………………………（ 11 ）
二、机械的内研磨………………………………………………………………（ 14 ）
第三节　沙割……………………………………………………………………（ 14 ）
第四节　沙埋……………………………………………………………………（ 15 ）
一、颗粒的沉积…………………………………………………………………（ 15 ）
二、沙丘前移压埋原理…………………………………………………………（ 17 ）
第五节　环境污染………………………………………………………………（ 20 ）
一、沙尘浓度对大气能见度的影响……………………………………………（ 21 ）
二、风沙电的形成和作用………………………………………………………（ 22 ）
第二章　沙粒运动力学………………………………………………………（ 24 ）
引言……………………………………………………………………………（ 24 ）
第一节　颗粒运动图象及其数理分析…………………………………………（ 25 ）
一、振动和滚动…………………………………………………………………（ 26 ）
二、滑移…………………………………………………………………………（ 28 ）
三、跃移…………………………………………………………………………（ 29 ）
第二节　颗粒的碰撞与旋转……………………………………………………（ 44 ）
一、碰撞分类与碰撞作用………………………………………………………（ 45 ）
二、旋转分类与旋转作用………………………………………………………（ 50 ）
第三章　风沙两相流体动力学………………………………………………（ 54 ）
引言……………………………………………………………………………（ 54 ）
第一节　风沙两相流体动力学方程组的建立…………………………………（ 55 ）
一、物理力学模型………………………………………………………………（ 56 ）
二、数学模型……………………………………………………………………（ 57 ）
第二节　动力学方程组的简化和求解…………………………………………（ 58 ）
一、进一步简化…………………………………………………………………（ 58 ）
二、求解与讨论…………………………………………………………………（ 60 ）
第三节　风沙运动实验相似理论………………………………………………（ 66 ）

第四节 风沙观测与验证 …… (68)
一、风沙流中的风速廓线 …… (68)
二、风沙流结构 …… (72)
三、颗粒流平均水平运动速度 …… (76)
第四章 风成床面形态的运动 …… (79)
引言 …… (79)
第一节 沙纹的运动 …… (79)
一、沙纹形成的假说 …… (79)
二、沙纹的分类 …… (81)
三、沙纹形成的实验研究 …… (82)
四、沙纹的发展与消亡 …… (95)
第二节 沙丘的运动 …… (97)
一、沙丘成因研究的历史回顾 …… (98)
二、二次流的作用与沙丘的形成发展 …… (102)
三、沙丘运动的风洞实验研究 …… (108)
第五章 风沙工程 …… (122)
引言 …… (122)
第一节 风沙工程的分类 …… (122)
第二节 风沙工程的力学作用原理和一般设计原则 …… (123)
一、封闭工程 …… (123)
二、固定工程 …… (124)
三、阻滞和拦截工程 …… (125)
四、输导工程 …… (128)
五、转向工程 …… (129)
六、消散工程 …… (131)
第三节 风沙工程实验的相似准则 …… (132)
一、纯气流运动 …… (133)
二、风沙流运动 …… (134)
三、风沙流条件下的风沙工程实验 …… (136)
第四节 典型风沙工程的风洞实验研究 …… (137)
一、草方格和粘土沙障工程 …… (138)
二、栅栏、林带和林网工程 …… (149)
三、下导风工程 …… (165)
四、羽毛排工程 …… (185)
五、输沙桥工程 …… (193)
六、输导沙断面工程 …… (205)
参考文献 …… (208)
图版 …… (210之后)

CONTENTS

Preface ………………………………………………………………………… (i)
Introduction ………………………………………………………………………… (v)
Chapter 1 Sand Drift Problem ………………………………………………… (1)
Introduction ………………………………………………………………………… (1)
Ⅰ. Wind Erosion ………………………………………………………………………… (1)
1.1 Damages of wind erosion ………………………………………………… (1)
1.2 Advance in wind erosion research ………………………………………… (2)
1.3 Principles of wind erosion ………………………………………………… (3)
Ⅱ. Abrasion ………………………………………………………………………… (11)
2.1 External abrasion of the object ………………………………………… (11)
2.2 Internal abrasion of the machinery ……………………………………… (14)
Ⅲ. Sand Cutting ………………………………………………………………………… (14)
Ⅳ. Sand Burying ………………………………………………………………………… (15)
4.1 Deposition of sand particles ……………………………………………… (15)
4.2 Burying principles of abvancing sand dunes ……………………………… (17)
Ⅴ. Environment Pollution ……………………………………………………………… (20)
5.1 Effect of sand-dust density to atmospheric visibility …………………… (21)
5.2 Formation and action of wind-sand electricity …………………………… (22)
Chapter 2 Mechanics of Sand Grain Movement ……………………………… (24)
Introduction ………………………………………………………………………… (24)
Ⅰ. Images of the Particle Movement and Their Mathematical Analysis ………… (25)
1.1 Vibration and rolling ……………………………………………………… (26)
1.2 Sliding ……………………………………………………………………… (28)
1.3 Saltation …………………………………………………………………… (29)
Ⅱ. Collision and Rotation of Particles …………………………………………… (44)
2.1 Classification and role of collision ……………………………………… (45)
2.2 Classification land role of rotation ……………………………………… (50)
Chapter 3 Dynamics of Two-phase Wind-Sand Fluid ………………………… (54)
Introduction ………………………………………………………………………… (54)
I. The Establishment of the Dynamical Equation Groups of the Two-phase Wind-Sand Fluid ………………………………………………………………………… (55)
1.1 Physio-mechanical model ………………………………………………… (56)
1.2 Mathematical model ……………………………………………………… (57)
Ⅱ. Simplification and Solution of Dynamical Equation Groups ………………… (58)
2.1 Consecutive simplification ………………………………………………… (58)
2.2 Solution and discussion …………………………………………………… (60)

Ⅲ. Similarity Theory in Wind-Sand Movement Experiments .... (66)
Ⅳ. Sand Drift Observation and Examination .... (68)
4.1 Wind profile of wind-sand flow .... (68)
4.2 Wind-sand flow structure .... (72)
4.3 Average horizontal movement velocity of particle flow .... (76)
Chapter 4 Movement of Aeolian Bedform .... (79)
Introduction .... (79)
Ⅰ. Sand Ripple Movement .... (79)
1.1 Hypothesis on the formation of sand ripples .... (79)
1.2 Sand ripple classification .... (81)
1.3 Experimental study of sand ripples .... (82)
1.4 Development and disappearance of sand ripples .... (95)
Ⅱ. Sand Dune Movement .... (97)
2.1 Historical retrospect on the study of sand dune formation causes .... (98)
2.2 Secondary flow action and sand dune formation and evolution .... (102)
2.3 Wind tunnel experimental study on sand dune movement .... (108)
Chapter 5 Sand Drift Control Engineering .... (122)
Introduction .... (122)
Ⅰ. Classification of Sand Drift Control Engineering .... (122)
Ⅱ. Mechanical Actions of Sand Drift Control Engineering and General Design Principles .... (123)
2.1 Mulching engineering .... (123)
2.2 Stabilization engineering .... (124)
2.3 Blockage and intercepting engineering .... (125)
2.4 Transferring engineering .... (128)
2.5 Direction-changing engineering .... (129)
2.6 Dissipation engineering .... (131)
Ⅲ. Similarity Principles in the Experiments of Sand Drifting Control Engineering .... (132)
3.1 Pure airflow movement .... (133)
3.2 Wind-sand flow movement .... (134)
3.3 Experiments on sand drift control engineering under wind-sand flow condition ... (136)
Ⅳ. Wind tunnel Experimental Study on Typical Sand Drift Control Engineering (137)
4.1 Straw checkerboard and clay barriers .... (138)
4.2 Fence, forest belt and forest net .... (149)
4.3 Bottom-deflecting sand fence .... (165)
4.4 Feather-like sand fence .... (185)
4.5 Sand-transporting bridge .... (192)
4.6 Sand-transporting cross section .... (205)
References .... (208)
Plates .... (After page 210)