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Subhasish Dey

Fluvial Hydrodynamics

Hydrodynamic and Sediment Transport Phenomena

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To my wife, Swastika, and children, Sibasish and Sagarika, for their unconditional love, patience and continued support

Foreword I

Various problems from the broad field of research on sediment transport, such as local scouring, sedimentation in reservoirs, erosion due to floods, dam breaching flows, aggradations, and degradations of riverbed are of fundamental importance for river engineers, geophysicists, decision makers, and environmentalists. At the same time, these problems are still far from being solved and constitute the basic issue for scientists dealing with environmental hydraulics. Even at microscale level, we realize that sediment particles respond to hydraulic forces such as shear and lift, whose effects are in turn related to basic hydrodynamic flow properties, particle size, shape, and density. Sediment transport can, in principle, be thought of as moving water exerting both lift and drag on sediment particles at rest and/or in motion. Although this concept is relatively simple numerous other, very often nonlinear, processes occur and quantitative modeling of sediment transport turns out to be extremely difficult. This is the result of the complexity of the physical processes that govern the particle transport in water bodies, manifold of important scales, meaningful uncertainties related to input data, knowledge gaps, and numerical difficulties.

This book brings together emerging perspectives from fluid mechanics, sediment transport theory, civil engineering, and mathematical modeling. Reflecting on the book's theoretical and empirical focus, the audience is two-fold: students and scholars working within the university tradition, and environmental scholars and engineers interested in solving real life problems. Together, this mix forms a creative synthesis for both sets of readers.

Although the problems of sediment transport have been studied for more than two centuries, there are not many up-to date reference books presenting the actual state of the art in the field. In view of this lack of readily available, clearly presented information, this volume fills an important void. Its analyses and discussions of also individual aspects provide the kind of basis that any student and specialist in the field would like to have in approaching this subject. It is thus a most welcome contribution to the growing body of literature on hydraulics, focusing exclusively on what is clearly the key area of concern.

Subhasish Dey has been a pioneer in the field of applied hydrodynamics, turbulence, and sediment transport. His journey in the world of science and engineering took him from the University of North Bengal through a number of stops at the Universität Stuttgart, Technische Universität Darmstadt, University of Iowa,

Technical University of Denmark, Adelaide University, University of Bradford, Chinese Academy of Science, Tsinghua University, University of Hong Kong, Università di Pisa, Università della Calabria, Politecnico di Milano, University of Florence, University of Oulu, Instituto Superior Tecnico Lisbon, National Taiwan University, National Chung Hsing University, National Cheng Kung University, Nanyang Technological University, Laboratoire Central des Ponts et Chaussées, and other academia, where he offered a course on sediment transport and/or stayed as a visiting professor, to his present home at the Indian Institute of Technology Kharagpur where he is the professor and head of the Department of Civil Engineering. This journey has given him a unique perspective on the thrilling field of sediment transport. I could personally experience his extraordinary passion and devotion to science having *Sub* (as I call him in short) as invited speaker during two international schools of hydraulics (2010 and 2012) that I had the privilege to chair. The contacts and the friendship struck up that time have brought fruit at enormous speed and we can now enjoy this fantastic tome.

Scientists and engineers working in the field of hydrodynamics, sediment transport, and related areas owe *Subhasish Dey* a debt of gratitude for producing this excellent volume. It will help young people entering the field and will serve as a valuable reference work for more experienced scientists. I believe that the field of sediment research will progress more quickly and vigorously as a result of the publication of this excellent book. This volume will also enormously enrich the Springer book series: *GeoPlanet: Earth and Planetary Sciences*.

Warsaw, March 2014 Pawel M. Rowinski

Foreword II

The traditional Fluvial Hydraulics has significantly transformed over recent decades moving from a largely empirical discipline towards a qualitatively new level of mathematically and physically rigorous methodologies of modern fluid mechanics. This step change has become possible due to the progress in modeling and experimental capabilities that led to significant advances in the understanding of the key processes involved in fluvial dynamics. The turbulence structure among them is particularly important as it is a fundamental driver of the interactions between turbulent flow and its erodible boundaries. As a reflection of these changes, the title of the discipline has changed from Fluvial Hydraulics to *Fluvial Hydrodynamics* and this book is an excellent highlight of this important transition.

Over the years, the author of this book has been among key players in the modernization of fluvial hydraulics by contributing on many fronts, from fundamental issues of open-channel flow turbulence to particle entrainment and transport. This personal involvement in the subject makes this book particularly interesting and stimulating.

The book joins a great family of recent texts on this topic, such as W. Graf and M. Altinakar (1998), A. Raudkivi (1998), G. Parker (2004), M. H. Garcia (1996, 2008), J. C. Winterwerp and W. G. M. van Kesteren (2004), A. Gyr and K. Hoyer (2007), E. Partheniades (2009), and A. J. Mehta (2013). Each of these books is unique and provides their own specific perspective on the subject. *Subhasish Dey*'s book continues this tradition and the author should be highly commended for his outstanding effort. I have no doubt that this book will help in training a new generation of civil and hydraulic engineers and will inspire new discoveries in hydraulic research.

Aberdeen, March 2014 Vladimir Nikora

Foreword III

This book, *Fluvial Hydrodynamics*, by *Subhasish Dey* is based on his teaching, laboratory research, and extensive field experience for more than 30 years. His practical knowledge along with a strong scientific background has enabled him to come up at this stage. This spirit impregnates to write this excellent book that contains a wealth of theoretical as well as applied material justifying a comprehensive treatise on hydrodynamics of sediment transport. I strongly believe that the book would be a standard textbook all over the world not only for postgraduate and research level students, but also for field engineers as a practical guide and supplementary engineering handbook.

Knoxville, March 2014 Thanos Papanicolaou

Foreword IV

The book *Fluvial Hydrodynamics* that comprehensibly addresses the issues of sediment transport by turbulent flow differs from most texts in this field. It deals with every aspect of hydrodynamics related to sediment transport and is important in the context of sediment research and practice.

The author *Subhasish Dey* is not only an excellent researcher and at the forefront of current understanding of sediment transport, but also reviewed a broad spectrum of scientific literature to bring to the audience of this text an excellent volume that is up-to-date in all respects.

Beijing, March 2014 Zhao-Yin Wang

Foreword V

…I thought and still so believe that a book of this title will be of great value to the upcoming generations. As is evident from the most detailed list of contents, the book covers all possible problems, which future engineers will be confronted in their professional career, but equally in research. The exercises, a special feature in the text, presented in the book will be very useful.

Lausanne, November 2013 Walter H. Graf

Preface

I come from haunts of coot and hern,
I make a sudden sally
And sparkle out among the fern,
To bicker down a valley.

By thirty hills I hurry down,
Or slip between the ridges,
By twenty thorpes, a little town,
And half a hundred bridges.

Till last by Philip's farm I flow
To join the brimming river,
For men may come and men may go,
But I go on forever.
…

The Brook, Alfred Lord Tennyson (1809–1892)

Flow in a *river* that *goes on forever* is one of the most evident manifestations of gravity. The river and its characteristics must be studied, must be understood. The book, *Fluvial Hydrodynamics*, goes in this direction written by an *unknown hydraulician*.

The state of the art in fluvial hydrodynamics can be examined only through a careful exploration of the theoretical development and applied engineering technology. This book is primarily focused, since most up-to-date primary research findings in this field are presented, on the research aspects that involve a comprehensive understanding of the mechanics and physics of sediment transport by turbulent flow. It begins with the fundamentals of hydrodynamic principles applicable to open-channel flow followed by turbulence characteristics related to sediment motion. Then, the sediment dynamics are described from a classical perspective by applying the mean bed shear approach, and additionally, incorporating a statistical description of the role of turbulence. The book also describes the local scour problems at hydraulic structures and scale models. It is thus intended primarily as a course textbook at the graduate/research level and also as a guide for field engineers, keeping up with modern scientific developments. Therefore, as a simple prerequisite, the readers should have a basic background knowledge in

hydraulics/fluid mechanics and an understanding of fundamentals of calculus, probability, statistics and physics.

In the field of civil engineering, where engineers typically learn about rivers in courses called open channel hydraulics and sediment transport, sound knowledge of fluvial hydrodynamics is important because it determines the aggradations and degradations of the river systems, life span of hydraulic structures and river protection works, etc. Thus, it is not surprising that this subject is of interest to a wide circle of professions that include hydraulicians, hydrologists, geologists, sedimentologists, geographers, civil engineers, environmental engineers, and so on.

I understand from the discussions with and comments from colleagues and students over the years during delivering lectures on an international short course on *turbulent flows, sediment transport and scour* offered to different universities around the world and on the regular graduate courses on *hydraulics of sediment transport* and *turbulent fluid flows* at my Institute (Indian Institute of Technology, Kharagpur) that the phenomena concerning the dynamics of sediment particles under a turbulent flow invite many open questions. My primary attempt is therefore to address the fundamental aspects of fluvial hydrodynamics from the viewpoint of micro-mechanical interaction of sediment particles with turbulent flow.

I am of the opinion that it could be possible to build a sound understanding of fluvial hydrodynamics on the typical foundation of fluid mechanics, basic calculus, probability, statistics and physics. Introducing new aspects found in the research of turbulent flow, this book updates the theories of sediment transport. It is therefore my hope that this book would close the gap between the micro-mechanics of sediment transport and the stochastic characteristics of turbulent flow. It differs from the traditional treatments of open channel hydraulics and sediment transport in its greater emphasis on the basic physics of turbulent flow in terms of quantitative analytical information.

A course based on this book would be appropriate for graduate and research students in hydraulic engineering and earth sciences curricula and would expected to be taught by a teacher with an active interest in this field. Under these circumstances, instructors would assign students in exploring questions that arise and in discussing papers from the journals, and to involve them in laboratory experiments and/or field studies. Therefore, I have also included exercises that can be used to explore the problems of practical importance involving complex hydrodynamic phenomena in the context of sediment dynamics. I would be greatly rewarded if this book proves to be of any assistance in improving existing scarcity of textbooks on sediment transport by turbulent flow.

I express my deep sense of indebtedness to *Pawel Rowinski*, Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland, who proposed and inspired me to write this book in his capacity as the Editor-in-Chief of the Springer book series: *Geoplanet: Earth and Planetary Sciences*. He was an endless source of help and encouragement. I heartily thank *Oscar Castro-Orgaz*, University of Cordoba, Spain for reviewing the manuscript at various stages in its development. I also thank *Walter Hans Graf*, Laboratoire de Recherches Hydrauliques, École Polytechnique Fédérale, Lausanne, Switzerland for his suggestions at the final stage of

the preparation of manuscript. Comments from *Pawel*, *Oscar* and *Walter* are extremely helpful to bring the manuscript to its final stage. Further, I am thankful to my graduate student *Sk Zeeshan Ali* for checking the manuscript thoroughly. However, I of course am solely responsible if there remain any errors and lack of clarity. Readers are however invited to communicate with me by giving suggestions on how the book can be improved in forthcoming editions. E-mails can be sent to me at *sdey@iitkgp.ac.in*

This work would not have been possible without the constant encouragement and support of my parents, *Kana Dey* (mother) and *Bimalendu Dey* (father), while pursuing my school level, undergraduate, and graduate education; and of my advisors of doctoral research, *Sujit K. Bose*, (former Professor) S. N. Bose National Centre for Basic Sciences, Kolkata, India, and *Ghandikota L. N. Sastry*, (former Professor) Indian Institute of Technology, Kharagpur, India, who most inspired and educated me.

The love, support, and encouragement of my wife *Swastika*, son *Sibasish*, and daughter *Sagarika* have sustained me in this work, as in every part of my life. Every human being owes a great deal to their friends and I am no exception. I treasure my close association with all my friends for their support, cooperation, and sincere help in various ways.

March 2014, Kharagpur Subhasish Dey

Contents

Chapter 1
Introduction

1.1 General

The term *fluvial* is commonly used in geophysics and earth sciences to refer to the processes associated with rivers or streams, and the erosions or deposits and morphology created by them. The subject *hydrodynamics* under the curriculum of civil engineering and environmental engineering becomes more diverse including the mechanism of the processes associated with fluvial systems. Fluvial processes comprise the sediment transport and aggradations or degradations of the riverbeds. The flow over a bed formed by the loose sediment exerts a shear stress on the bed. If the stabilizing resistance to the sediment particles is lower than the bed shear stress exerted, the sediment can be mobilized. For each particle size, there is a specific velocity or bed shear stress at which the particles on the bed surface start to move, called the *threshold velocity or threshold shear stress*, respectively. Sediment transport by the stream flows can occur in different modes. Sediment in rivers is transported as *bed load* (coarser fractions which move close to the bed) and/or *suspended load* (finer fractions carried by the flow). There is also a component carried as *wash load* that remains near the free surface of flow. Little is known specifically about the wash load where it comes from or where it goes. Further, during the sediment transport, the riverbed takes different undular features, called the *bedforms*. All these related to sediment transport make the flow in a river rather intricate, as compared to that in a rigid-bed channel. Further, the flow in rivers is locally modified by the embedded obstacles, such as bridge piers, abutments, and pipelines and the hydraulic structures, such as barrages, drops, and sills. The modified flow has enormous erosive potential causing a *local scour* near the obstacles and the hydraulic structures.

A natural river continually picks up sediment from and drops sediment on its bed throughout its course. Where the river flows with high velocity, more sediment is picked up than dropped. In contrast, where the flow is tranquil, more sediment is dropped than picked up. These processes including the formations of bedforms, such as ripples, dunes, and antidunes, determine the complex morphology of a river. In a typical river, the largest carried sediment is of sand and gravel size, but a

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larger flood can carry cobbles and even boulders. The amount of sediment carried by a large river is enormous. For instance, the Mississippi in USA annually carries 406×10^6 tons of sediment to the sea, the Hwang Ho in China 796×10^6 tons and the Po in Italy 67×10^6 tons.

The origin of the development of *fluvial hydrodynamics* dates back to the distant past, as people faced the problems due to erosion, sedimentation, and floods. The ancient civilizations particularly in the valleys of Indus, Tigris, Euphrates, Nile, and Hwang Ho rivers used the unlined canals for irrigation. Historical records suggest that about six thousand years ago, marginal embankments were built along the Hwang Ho in China; irrigation canals and flood control structures constructed in Mesopotamia; and one thousand years afterward a masonry dam built across the Nile in Egypt. In India, more than five thousand years ago, the mechanics of sediment transport by stream flows was explained by *sage Vashistha*. During the Renaissance era, famous Italian painter and scientist-cum-engineer *Leonardo da Vinci* made the first empirical studies of streams and their velocity distributions. His notebooks are full of observations that he made on rivers; and they reveal that he understood the principles of sedimentation and erosion. Since then, scientists and engineers have performed a large number of studies on rivers.

The subject *fluvial hydrodynamics*, being important in the fields of civil engineering, environmental engineering, sedimentary geology, and earth sciences, is most often used to know whether erosion or deposition of sediment or even transport of sediment can occur. If so, what are the magnitude of erosion or deposition and the duration or transport rate? Even though enormous efforts have been made by scientists and engineers to resolve various problems related to sediment transport, due to inherent complexities involved in sediment transport processes and difficulties in taking accurate measurements, inadequate landmark breakthroughs have so far been achieved on a sizable number of key problems. As such, the knowledge on such complex problems is still limited to the perceptual state. Therefore, the research on sediment transport should be directed in solving problems, that often arise in practice involving inherent complex phenomena.

Knowledge of sediment transport can be applied extensively in civil engineering such as to plan the extended life of a dam forming a reservoir. Sediment carried by a river deposits into a reservoir formed by a dam developing a reservoir delta. The delta grows with time filling the reservoir to reduce its capacity, and eventually, either the reservoir needs to be dredged or the dam needs to be abandoned. Also an adequate knowledge of the mechanics of sediment transport in a built environment is important for civil and hydraulic engineers. Flow in culverts, over spillways, below pipelines, and around bridge piers/abutments creates scour, which can damage the environment and expose the foundations of the structures being detrimental to them.

Sediment transport, being applied in solving various environmental engineering problems, is important in providing habitat for fish in rivers and other instream organisms, sustaining a hygienic stream ecosystem. On the other hand, when suspended load of sediment is substantial due to human activities, it can cause environmental hazards including the filling up of the channels by siltation.

Geologists, on the other hand, seek inverse solutions for sediment transport relationships to get an idea on the flow depth, velocity, and direction, from the characteristics of the sedimentary rocks and new deposits of sediment particles.

1.2 Scope of this Book

The aim of the science of fluvial hydrodynamics is to understand the behavior of sediment transport in natural streams and to provide a basis for predicting its responses to natural or man-made disturbances. However, in general, the basic problem of flow over a sediment bed can be stated in a rather deceptively simple way: Given the sediment characteristics, flow rate and bed slope; what are the probable flow depth and the sediment transport rate? Even for the simplest case of a two-dimensional flow over a flat bed formed by a uniform sediment size, a general solution can only be presented with estimates involving high degree of uncertainty, as much of the intricacy lies on velocity or turbulent stress distribution over a sediment bed. Advances in measurement technology and progress in understanding of the turbulence phenomena in shear flow within near-bed flow region inspire recent research trend that may append to a more satisfactory response to the basic questions. Moreover, this topic has attracted the attention not only of engineers but also of earth scientists, with potentially constructive results and contributions being published in leading journals, reports, and monographs not essentially familiar to the hydraulic engineering communities.

The objective of this book is therefore to develop a sound qualitative and quantitative basis of knowledge of the subject. This book is rather different from a typical engineering treatment of open-channel flow in its larger emphasis on fluvial streams and their interactions with structures, such as, bridge piers and abutments, bed sills. It also differs from a general earth science-oriented treatment in its extended emphasis on the analyses based on the physics of turbulent flow and its customary applications developed for engineering practices. To be useful, a special attempt is made in this book to include the new important research results on sediment transport achieved over the past years. It seems to be a demand, as over decades, there have been inadequate efforts in incorporating of new developments that help to predict sediment transport processes more accurately and are also helpful in field situations not so far included in the traditional textbooks.

1.3 Coverage of this Book

The topics of this book include hydrodynamic principles and turbulence characteristics related to open-channel flow, mechanics of sediment transport, and local scour phenomena including application examples in fluvial hydrodynamics. It is organized into eleven chapters. They are as follows:

This chapter provides an introduction to the fluvial hydrodynamics, scope and outline of this book, and the properties of fluid and sediment. Chapter 2 introduces the fundamental theories of hydrodynamics in the context of open-channel flow. Chapter 3 presents the turbulence characteristics in flow over a sediment bed. It includes most of the modern development of turbulent flow, such as bursting phenomenon, double averaging of heterogeneous flow over gravel-beds. Chapter 4 is devoted to the theories of the initiation of sediment motion. It encompasses different concepts of sediment threshold and their theoretical and empirical developments. Chapter 5 describes the concepts, theories, and empirical formulations of bed load transport and saltation, while Chaps. 6 and 7 illustrate those of suspended and total load transports, respectively. Chapter 8 demonstrates different types of bedforms and their mechanism of formation and resistant to flow. Chapter 9 describes the natural fluvial processes toward meanderings and braiding. Chapter 10 outlines comprehensive information on local scour within channel contractions, downstream of structures, below horizontal pipelines, at bridge piers and abutments, and scour countermeasures. Chapter 11 is designed to deal with the issue to describe dimensional analysis, modeling, and similitude of sediment transport and scour problems.

The general feature of all the chapters is shaped by the fundamentals, such as the definitions of the phenomena and the involved parameters as well as a series of methodologies, starting from the earlier developments and ending to the latest ones.

In the end of each chapter, bibliographical references are given.

1.4 Physical Properties of Fluid and Sediment

Following properties of fluid and sediment are of general importance to study the fluvial hydrodynamics. For the convenience, typical values, SI units, and dimensions in MLT system (also see Chap. 11) are given.

1.4.1 Mass Densities of Fluid and Sediment

The *mass density* ρ of a fluid is defined as its mass per unit volume. The mass density at a point is determined by considering the mass dm of a small volume dV surrounding the point. As dV becomes a magnitude ε^3, where ε is the small linear distance but larger than the mean distance between molecules, the mass density at a point is given by

$$\rho = \lim_{\mathrm{d}V \to \varepsilon^3} \frac{\mathrm{d}m}{\mathrm{d}V} \tag{1.1}$$