Unsteady Flow in Open Channels

From river floods and tides, to systems for drainage and distribution of water, flows in open channels affect the daily lives of many people. Practitioners in water engineering rely on a thorough understanding of these flows in order to safeguard our habitat, while at the same time sustaining the water environment.

Unsteady Flow in Open Channels provides a coherent approach to the analyses and modelling of various types of unsteady flow, highlighting their similarities and differences. It presents a unified framework, using the relative roles of inertia and resistance to classify the different types of unsteady flow in environmental water systems. The link between analytical approaches and numerical modelling is emphasized – in particular, demonstrating how high-level computer languages, such as Python, can be used to solve advanced problems.

Every major topic in the book is accompanied by worked examples illustrating the theoretical concepts. Practical examples, showcasing inspiring research and engineering applications from the past and present, provide insight into how the theory developed. The book is also supplemented by a range of online resources, available at www.cambridge.org/battjes, including problem sets and computer codes. A solutions manual is also available for instructors. This book is intended for students and professionals working in the field of environmental water systems, in areas such as coasts, rivers, harbours, drainage, and irrigation canals.

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Contents

List of Symbols

Roman Symbols

a	acceleration of fluid particle (Chapter 2)
a	height of sharp-crested weir above upstream bed level (Chapter 9)
a	height of opening under a gate (Chapter 9)
A	area of entire wetted cross section
A_c	area of wetted conveyance cross section
b	binormal coordinate
B	width of the free surface
B_c	width of the free surface of the conveyance cross section
c	velocity of propagation of a disturbance relative to the fluid ahead of it
c	concentration of dissolved or suspended matter (Chapter 10)
c_D	wind drag coefficient
c_f	boundary resistance coefficient
c_{HW}	velocity of propagation of a flood wave
C	Chézy coefficient
d	cross-sectionally averaged depth of conveyance cross section ($d = A_c/B_c$)
d_{cr}	critical depth
D	grain or stone diameter (Chapter 9)
D	inner pipe diameter (Appendix A)
E	energy level above local bed elevation (Chapter 9)
E	Young's modulus of elasticity of pipe wall material (Appendix A)
F	energy flux
Fr	Froude number
F_r	resistance force
g	acceleration of gravity
h	elevation of the free surface above reference plane
h_p	piezometric level above reference plane
H	energy level above reference plane
i	imaginary unit
i_b	bed slope
i_f	friction slope

i_s slope of free surface
k wave number in harmonic wave or oscillation ($k = 2\pi/L$) (Chapters 3 and 7)
k Nikuradse sand grain diameter (Chapter 9)
K diffusivity in flood waves (Chapter 8)
K diffusivity in transport of matter (Chapter 10)
K modulus of compressibility of water (Appendix A)
ℓ length of basin
L wave length
$\mathcal{L}$ length scale of the motion
m discharge coefficient
n Manning's n
p fluid pressure
p complex root of dispersion equation ($p = \mu + ik$) (Chapter 7)
p_{atm} atmospheric pressure at the air–water interface
P wetted perimeter of conveyance cross section
P complex propagation constant in harmonic wave propagation (Chapter 7)
q discharge per unit width ($q = Q/B_c$)
Q discharge
r radius of curvature of a streamline (Chapter 1)
r ratio of wave heights at abrupt channel transition (Chapters 4 and 7)
r amplitude response factor (Chapters 6 and 7)
R hydraulic radius ($R = A_c/P$)
$R^{\pm}$ Riemann invariants
s streamwise coordinate
S relaxation length in theory of damping of translatory waves
t time
T wave period
$\vec{T}$ three-dimensional transport vector
$\mathcal{T}$ time scale of the motion
u local particle velocity
u_* shear velocity
U cross-sectionally averaged streamwise particle velocity u_s
$\mathcal{U}$ velocity scale of the motion
V velocity of propagation relative to the bed ($V = U + c$)
W total head loss in inlet–bay system
W_{10} wind speed (10-minute average at 10 m above mean water level)
x horizontal cartesian coordinate
y horizontal cartesian coordinate
z vertical cartesian coordinate, positive upward
Z complex auxiliary length representing the discharge in harmonic wave propagation

Greek Symbols

α	velocity distribution coefficient in momentum flux (Chapter 1)
α	dimensionless parameter of the free-surface profile of a translatory wave (Chapter 4)
α	arbitrary phase angle
β	angle of bed elevation with respect to the horizontal (Chapter 1)
β	velocity distribution coefficient in energy flux (Chapter 9)
β	arbitrary phase angle
γ	ratio of Bc-values at abrupt transition
Γ	dimensionless parameter in tidal inlet–bay system
δ	resistance angle in propagation of harmonic waves (Chapter 7)
δ	wall thickness (Appendix A)
ϵ	infinitesimal dimensionless quantity
ϵ	molecular diffusivity (Chapter 10)
ϵ_t	turbulence diffusivity (Chapter 10)
ζ	surface elevation above mean water level
η	dimensionless value of ζ
θ	phase lag of bay tide behind exterior tide
κ	resistance factor with dimension 1/time in harmonic wave propagation (Chapter 7)
κ	Von Karman constant in theory of turbulent boundary layers (Chapter 10)
μ	damping modulus in harmonic wave propagation (Chapter 7)
μ	contraction coefficient (Chapter 9)
ν_t	kinematic turbulence viscosity
ξ	head loss coefficient
ρ	water density
ρ_a	air density
σ	dimensionless resistance factor in harmonic wave propagation (Chapter 7)
σ	streamwise standard deviation of surface elevation in flood waves (Chapter 8)
σ	standard deviation of concentration of transported substance (Chapter 10)
σ	Courant number (Chapter 11)
Φ	Gaussian probability density function
τ	relaxation time in inlet–bay system
τ_b	boundary shear stress
τ_s	wind shear stress at the free surface
χ	coefficient for expansion loss and boundary resistance in inlet–bay system
Ψ	angle between wind direction and flow direction
ω	radial frequency in harmonic motion ($\omega = 2\pi/T$)
ω_0	natural (Helmholtz) frequency of inlet-bay system

Diacritical Marks

$\hat{\circ}$	circumflex	(real) amplitude of a quantity
$\tilde{\circ}$	tilde	complex amplitude of a quantity
$\bar{\circ}$	macron	(turbulence) quantity averaged over time or space
$\circ'$	prime	(turbulent) fluctuation of a quantity
$\circ'$	prime	first derivative of a function
$\circ''$	double prime	second derivative of a function

Sub- and Superscripts

subscript s	refers to *sea*
subscript b	refers to *basin* or *bay* or *bed*
subscript c	refers to *conveyance* (area or width)
subscript 0	refers to an initial or undisturbed flow state
subscript 0	refers to quantities of a harmonic wave in the absence of resistance
subscript cr	refers to *critical* flow
subscript u	refers to *uniform* flow
superscript $+$	refers to propagation in *positive* s-direction
superscript $-$	refers to propagation in *negative* s-direction

Preface

This book grew out of lectures on unsteady flow in open channels in the Civil Engineering Department of the Delft University of Technology for senior BSc students and first-year MSc students in hydraulic and coastal engineering, water resources management, hydrology and sanitary engineering. It deals with gradually varying, unsteady flows, or long waves, in natural channels such as rivers, estuaries and tidal channels, as well as man-made canals for various purposes such as drainage and irrigation systems and shipping.

Most existing books on open channel flow deal mainly with steady flows, unsteady flows typically being diverted to a single chapter. In practice, unsteady flows are the rule rather than the exception. Therefore, a unified introduction was deemed necessary, in which the unsteadiness and the important associated notion of wave propagation are essential ingredients from the start. The intended readership consists of students in the above-mentioned disciplines as well as practitioners.

Subject

The subject of this book is the mathematical modelling of gradually varying unsteady flows, or long waves, in open channels. Various classes of long waves are distinguished, depending on their origin and the associated time scale, varying from the relatively rapid translatory waves to the sluggish flood waves in lowland rivers. A chapter on steady flow summarizes some relevant results within this subclass. Transport of dissolved or suspended matter in open channels is briefly dealt with as well. Lastly, the numerical modelling of flow in conduits is covered in a separate chapter.

Pressurized flow in pipelines falls formally outside the scope of this book, but it is included nonetheless because pipe flow often is an integral part of water transport systems, and the mathematical equations describing pressurized flow and those describing open channel flow are quite similar. For these reasons, a summary is presented in Appendix A.

Aim

This book offers a unified presentation of the mathematical modelling of various classes of unsteady flows that can be expected in the context of design and operation of hydraulic engineering works in tidal areas, estuaries, rivers, canals etc., e.g. dredging or the construction and operation of control structures or dams. The engineer should be able to foresee consequences of the works being designed, both qualitatively and quantitatively. This requires insight into these flows and the ability to schematize them, quantify them through mathematical modelling and computations and interpret the results. The achievement of these objectives is the primary aim of this book.

In view of the above, the more specific aims of this book can be summarized as follows:

- to provide qualitative knowledge of various classes of unsteady flow phenomena in open channels that are important in engineering practice
- to provide insight into the relative importance of various mechanisms in the dynamics of these flows
- to explain the physics of shallow-water wave propagation
- to stimulate an attitude of making a (qualitative) problem analysis including the estimation of relevant effects
- to offer a unified, systematic overview of mathematical approximations and solution methods suited to various categories of open channel flow
- to enable the reader to develop the ability to make schematizations and to perform approximative computations for the flow phenomena considered
- to develop the ability to code algorithms for the computation of unsteady open-channel flows

Approach

A key characteristic of this book is its emphasis on the development of physical insight. This is approached through the presentation of simplified models of the principal classes of flow considered and the corresponding analytical solutions, since these show explicitly the effects of the major parameters involved.

Following the derivation of the basic one-dimensional equations for long waves (the so-called shallow-water equations), distinct classes of waves are presented and discussed. For each of these, order-of-magnitude relations between the different physical processes are derived, including the boundary resistance relative to the inertia. In fact, the latter ratio is used as the ordering principle for the remainder of the book, the successive chapters dealing with a class of flows of increasing relative resistance, going from translatory waves with negligible resistance to friction-dominated flood waves in lowland rivers.

In each of these chapters, the presentation proceeds from a qualitative discussion, via the introduction of appropriate simplifications of the momentum equation, to the development of a quantitative mathematical model. Analytical solutions are presented because these are optimally suited to the development of physical insight. The aim in these chapters is not to develop models of high quantitative accuracy. This is done in a final chapter, exclusively devoted to numerical modelling.

In view of its importance, understanding of the notion of wave propagation is developed gradually. A qualitative description of the propagation of low frictionless translatory waves in prismatic conduits prepares the way to the derivation of the corresponding general linear wave equation. Subsequently, these restrictions are gradually relaxed by considering variations in channel cross section, allowing finite wave heights, and incorporating friction. The method of characteristics is introduced next to provide added understanding as well as a formal mathematical framework for quantitative evaluations.

The practical relevance of the developed concepts is demonstrated with examples from inspiring engineering cases (such as the enclosure of the previous Zuiderzee in The Netherlands) and captivating natural phenomena (e.g. tidal bores). Field observations and some laboratory data are presented for a quantitative comparison with the theory.

Worked-out examples are presented for purposes of illustration, to provide more understanding and to aid in the ability to apply the theory. Each chapter ends with a set of Problems.

Layout

Chapter 1 opens with a brief description of the approach to the mathematical modelling of unsteady flow in open channels. This is followed by a presentation of the basic equations for these flows, which are the starting point for the analysis and modelling of various categories of long waves in the following chapters. Chapter 2 describes several characteristic long-wave phenomena qualitatively and presents a quantitative analysis of their major characteristics, making visible which processes are dominant and which ones are relatively weak in the various categories of long waves.

The notion of wave propagation with neglect of the effects of resistance is developed in Chapters 3 and 4, followed by the introduction of the powerful method of characteristics in Chapter 5.

Chapters 6–8 present suitable mathematical approximations for several classes of long waves. Corresponding solution techniques and solutions are presented as well. Harmonic motions are considered in Chapter 6 for standing oscillations in basins and in Chapter 7 for propagation with friction, mainly aimed at tidal propagation, in which resistance is important but not dominant. Flood waves in lowland rivers, in which inertial effects can be neglected relative to resistance, are the subject of Chapter 8.

Chapter 9 gives a brief summary of the modelling of steady flows, again in the order of increasing slowness, viz. rapidly varying steady flow through control structures, gradually varying steady flows (backwater curves) and finally uniform flow, which in essence is a summary of expressions for boundary resistance. Chapter 10 presents an introduction to the modelling of transport processes. Principles of numerical modelling of unsteady flows in open channels are dealt with in Chapter 11.

Lastly, Appendix A covers pressurized flow in pipes. A summary of equations is presented in Appendix B.

Prior Knowledge

The treatment of the various subjects relies on prior knowledge of basic fluid mechanics and an understanding of ordinary and partial differential equations and complex algebra.

Awareness of civil engineering will help in the understanding of the book, but this is not considered essential. The book includes some worked examples using simple computer code (written in Python) for which basic programming skills will be useful. These may also be learned, however, by following along with the examples.

Course Plan

Teaching all of the material covered in the book will take some 24–36 lectures of $1\frac{1}{2}$ teaching hours each, depending on the depth at which the various topics are treated and the expected self-study effort. When scheduled during a full semester, the course will typically take two lectures per week, while an additional 3–4 hours will be required weekly for self-study. Including exam preparation (2 days), the total work load for the student will amount to about 170 hours.

Chapters 1–8 are considered the backbone of the course. Related topics are dealt with in Chapters 9–11. The latter are often part of other, more dedicated, courses, in which case they can be omitted from the course plan. This will reduce the total working load to about 120 hours. The reduced course would also fit nicely into a half-semester schedule consisting of three lectures a week and 5–6 hours of self-study.

For self-study rehearsal every chapter concludes with a series of Problems for which a solutions manual is available separately. General solution strategies are explained in the worked examples preceding each Problems section. A series of digital exercises is available for the reader to become familiar with the concepts of the corresponding topic and to practise, progressively, the required skills. They also include so-called diagnostic tests, to assess one's preparedness for the exam.

Literature

The mathematical models for the considered long-wave categories presented in this book are classical (with a few exceptions for an extension of the theory). Thus, no references are made to individual contributors. Instead, we refer to the textbooks on the subject listed below, to which we are much indebted. Only in cases of very specific results, and in cases where results bear the name of the originator, have individual references been given.

Chaudry, M. H. 1993. *Open-Channel Flow.* Prentice Hall.

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Henderson, F. M. 1966. *Open Channel Flow.* Macmillan.

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Supplementary Materials

The book comes with a collection of supplementary materials, which is available online. Included are a solutions manual for the Problems at the end of each chapter, a series of digital tests (for use in a MapleTA environment), and some Python scripts for carrying out the computations and Problems of Chapter 11.

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