Hu Huang

Dynamics of Surface Waves in Coastal Waters

Wave-Current-Bottom Interactions

海岸水域表面波动力学

波–流–海底相互作用

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Hu Huang

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To my youthful father and mother
devoting all their lives to The Xinjiang Production and
Construction Corps in China since September 25th 1949

Preface

Water waves hold up a great mirror to one man and let him look at himself in his billowing blue sky.

Wave motion surrounds us—from the most secret, profound waves of quantum mechanics to the grand waves of the ocean surface.

Ocean waves, or water waves, may be divided into deep- and shallow- water (coastal) waves. From an advance point of view, coastal waves are not studied as thoroughly as deep-water waves due to a complicated seabed topography on the former but not on the latter. Therefore, in conjunction with the effects of ubiquitous ambient currents, wave-current-bottom interactions make up the most fundamental, widespread dynamical mechanism in coastal waters manifesting itself as refraction, diffraction, scattering, and resonant wave interactions involved in energy exchanges.

Apparently, it is essential to obtain a full, clear explanation and description of coastal waves for the development of broad offshore, coastal and harbor engineering, and also for having a better understanding of the evolutionary mechanism of deep-water waves. In fact, a commanding view on long-term investigating water waves is to wholly and uniformly treat and describe deep- and shallow-water waves, thus promoting the present rapid exploration and development of global oil and gas fields in deep waters of the oceans.

The aforementioned views, ideas, judgments, all that I have thought and done over the last ten years, were compiled by me in this book. The book consists of nine chapters and appendices from A to H, depicting the fundamental paradigms of weakly nonlinear water waves.

Chapter 1 makes a concise, historical review of water wave theories with the emphasis on current mild-slope equations and Boussinesq-type equations. An outline of three kinds of fundamental formulations of the surface water wave problems then follows.

Chapter 2, on the Liu-Dingemans evolution equations, gives a modification to that, and extensions of that, from third- to fourth-order with stability analysis, and from pure waves to wave-current interactions.

Chapter 3 deals with resonant wave-current-bottom interactions, concentrating on subharmonic resonance concerning the modulated wave groups and second-order long waves.

Chapter 4 is dedicated to six kinds of the mild-slope equations depending on the variation of ambient currents and bottom topography. In particular, a new type of conservative quantity, the product of phase velocity and group velocity, is put forward, and an operator indicating wave-current interaction is introduced to develop a hierarchy of the mild-slope equations.

Chapter 5 addresses linear gravity waves over rigid, porous bottoms by formulating two different models involving the mild-slope equations and the general variation of the wave continuity.

Chapter 6 leads to a type of nonlinear unified equations suitable for an uneven bottom, containing four kinds of major equations and theories as special cases.

Chapter 7, taking into account the Coriolis force and moving bottoms, bears on a generalized mean-flow theory for waves on currents, thus creating three new kinds of wave actions.

Chapter 8, on Hamiltonian stratified wave-current interactions, covers three kinds of stratified fluid systems with a number of the canonically conjugate variables.

Chapter 9 is the longest and devoted to short-crested waves (SCWs), perhaps the simplest genuinely three-dimensional water waves. The incompatibility involving standing waves and SCWs is found and effectively solved. Then, linear, first-, second- and third-order theories for pure gravity and capillary-gravity SCWs with or without ambient currents are respectively established in great detail, involving wave forces essential to engineering applications.

This book is aimed at researchers and graduate students specializing in coastal and ocean engineering, physical oceanography, fluid mechanics and applied mathematics, and at all those who wish to obtain a proper understanding of coastal dynamic processes.

Naturally, this book will not always stay "up-to-date" in terms of this research, but it can make a basic contribution to coastal wave investigations. Practically, what the monograph, acting as a courier, wants to become is nothing but my first battle call for the two great things not sought or conjectured by Immanuel Kant in 1788: *the starry heavens above me and the moral law within me.*

Hu Huang
Shanghai
April 2009

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About the Author

Hu Huang was born on March 2, 1964 in Shihezi, the Xinjiang Uygur Autonomous Region of China, belonging to the second generation of the Xinjiang Production and Construction Corps.

Huang is a professor of fluid mechanics and coastal surface wave dynamics at Shanghai University. He was an undergraduate student in irrigation and water conservancy engineering at the Shihezi Institute of Agriculture (1982–1986), and received his Master of engineering in experimental mechanics in 1993 and his PhD in coastal engineering in 1998, both at Tianjin University. He was a National Science Foundation Postdoctoral Fellow at the State Key Laboratory of Estuarine and Coastal Research, the East China Normal University (1998–2000). He had previously taught at the Xinjiang Shihezi Secondary Specialized School of Land Reclamation and Cultivation (1986–1990), and Tianjin University (1993–1998).

Huang's research interests focus on mechanics and symmetry, Hamiltonian mechanics, the dynamics of coastal and ocean surface waves, and applied mathematics.

Among Huang's honors and recognitions are: the first recipient of the Second Prize in Natural Science of the Ministry of Education of China in 2002 (No. 2002–063), a recipient of the National Excellent Doctoral Dissertation of China in 2004 (No. 2004028), and the Special Bonus of the State Council of China in 2004 (No. (02) 9310004).

Contents

1
Preliminaries

The history of the study on surface water waves, from the early work in 1687 by Newton to the pioneer resonant interaction theory in 1967 by Phillips, is briefly reviewed first, involving two important coastal current models: one-equation model—the mild-slope equation and its variants approximating the vertical structure of surface waves and averaging over variable depth; a shallow water approximation—the Boussinesq-type equations which reduce a three-dimensional problem into a two-dimensional one. Then three kinds of the formulations on surface water wave problems, i.e. the classical, the Lagrangian and the Hamiltonian, are described in outline.

1.1 Water Wave Theories in Historical Perspective

70.8% of the earth's surface is covered by oceans, the great theoretical and practical importance of water waves cannot be overestimated. Surface water waves, subjected to gravity force, surface tension, and other forces, are the most easily observed and studied; however, there is still a lot we don't know about these waves, particularly in coastal waters where uneven bottom topography plays a distinctive and vital role in wave propagation.

Historically [9], the subject of water waves traces back to the work by Newton in *Principia* (1687), against hydrostatics by Archimedes in 3 B. C. Much later, while accompanied by nonlinear water waves considered by Gerstner, the linear wave theory reached a real level of advances by the works of Laplace, Lagrange, Poisson, and Cauchy. Following this is the period of substantial contributions by Russell on the nonlinear solitary experiments, Green, Kelland, Airy on the nonlinear shallow water equations, and Earnshaw. Then, publishing his great paper in 1847 [42], Stokes ushered in a new era of his own weakly nonlinear water waves [9,10]. Later, the KdV equation of an important development appeared explicitly in 1895 by Korteweg and de Vries, but implicitly in 1872 by Boussinesq [33], that is, the Boussinesq equations.

Modern water wave theory began with weak, nonlinear interactions among gravity waves on the surface of deep water [36], which were confirmed and extended by Hasselmann [15], subsequently culminating in the Zakharov formulation or the wave turbulence theory [24,41,46–48] incorporating the effects of cubic or quartet interactions without limitations on spectral width on deep-intermediate water. In shallow coastal water, the nonlinear wave field is dominated by near-resonant quadratic interactions involving triplets of waves. It is the main wave-current-bottom interactions that have made rich and progressive coastal wave modeling since the late 1960s, albeit less mature relative to the well-established deep-water wave models [18,23]. At present, there is a wide variety of viewpoints to describe coastal water waves, such as the linear and nonlinear, the deterministic and stochastic, the time and frequency domains, the phase-resolving (for rapidly varying waves) and phase-averaged (for slowly varying waves), and parabolic approximation.

An overview of the current main and typical coastal wave models is as follows.

1.1.1 The Mild-Slope Equations

Linear theory all along plays a guiding and basic role in constructing theories. Take the mild-slope equations for example. The mild-slope equations simplify the refraction and diffraction of the linear surface waves in water of intermediate, variable depths by approximating the vertical structure of the motion in which a specific, preselected, depth function that corresponds to propagating waves in water of constant depth is adopted, and averaging over the depth by a vertical integration concerned essentially with Galerkin's method and variational principles. The original mild-slope equation was derived independently by Eckart [12], Berkhoff [5], and Smith and Sprinks [40]. Many of its extended counterparts have since been added, but most of them deal with pure wave motion apart from a few extensions on wave-current interactions by, for example, Kirby [21]. Huang [17] recently showed that the classical mild-slope equation of Berkhoff [5], the mild-slope equation for wave-current interactions by Kirby [21], the modified mild-slope equation by Chamberlain and Porter [7], and the hierarchy of partial differential equations by Miles and Chamberlain [34], can arise from an elaborate system of approximations to wave-current interactions over uneven bottoms.

Because any one-equation model cannot capture all features of the problem, the coupled-mode system, an infinite set of coupled equations, has been investigated by presenting a multi-mode approximation, such as the evanescent mode, the bottom mode, and the propagating wave mode [3,8,30,38].

Some recent entries into extensive literature in the linear mild-slope equations are provided in [11,16,20,25,37].

There also exist a number of deterministic and stochastic nonlinear mild-slope equations involving resonance in both wave-wave interactions and wave-bottom interactions played dominantly by Bragg scattering [1,2,13,19,43].

1.1.2 The Boussinesq-Type Equations

Boussinesq (1872) once advanced a theory for shallow water waves over a horizontal bottom, much later it was developed to the classical Boussinesq equations for an uneven bottom by Mei and LeMéhauté [31], Madsen and Mei [28], and Peregrine [35]. The current Boussinesq-type equations, featuring prominently in reducing the three-dimensional problem to a two-dimensional one, have attracted considerable attention over the past 20 years, thus giving rise to a number of enhanced and higher-order Boussinesq-type equations with the objective of improving linear and nonlinear properties [22,27,29], and allowing for wave propagation in almost all finite water depths.

Theoretically, Boussinesq-type equations are rich in almost every aspect of wave transformation over variable depth and in ambient (depth-uniform) currents, such as short-crested waves [14]. It is probably the richness that has practically made the present higher-order Boussinesq-type equations dauntingly complex in form. What should be the next step in the right direction by comparison with directly using the Navier-Stokes equations?