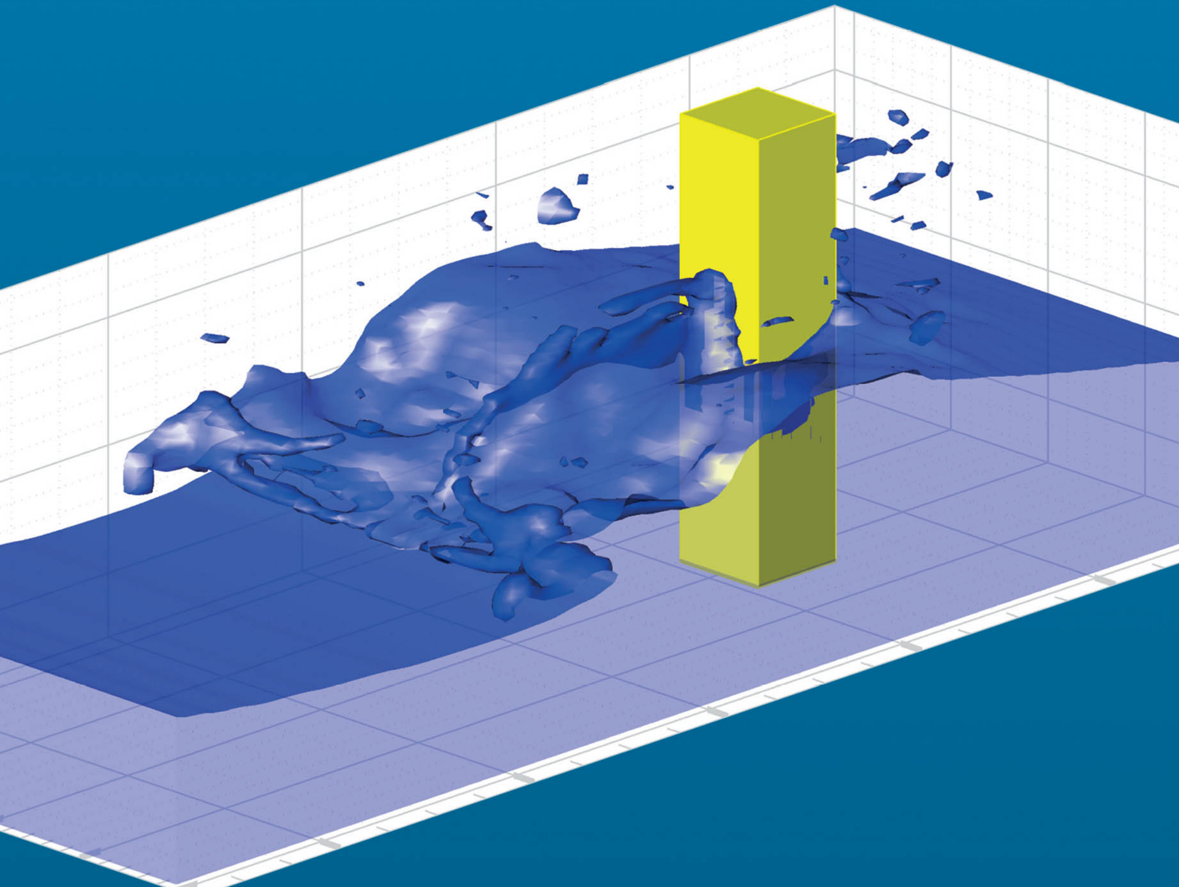
NUMERICAL MODELING OF WATER WAVES

PENGZHI LIN



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Contents

Preface

Water wave problems are of interest to coastal engineers, marine and offshore engineers, engineers working on naval architecture and ship design, and scientists working on physical oceanography and marine hydrodynamics. The theoretical study of water waves can be traced back to two centuries ago. In the past few decades, research in water waves has been very active, driven by the increasing demand of sea transport and offshore oil exploration. Various water wave theories have been developed to describe different wave phenomena. These wave theories enable us to understand the physical mechanisms of water waves and provide the basis for various water wave models.

Historically, the techniques of water wave modeling were developed in mainly two areas, coastal engineering and offshore engineering (including naval architecture). While the traditional wave modeling in coastal engineering has emphasised detailed wave transformation over a rigid and fixed bottom or structure, the wave modeling in offshore engineering and naval architecture has focused on wave loads on relatively large bodies and the corresponding structure responses. In recent years, there has been a trend to couple the modeling of complicated wave transformation (e.g., wave breaking) with the analysis of body motion. Furthermore, efforts are also being made to develop general-purpose models that can be applied not only to water wave problems, but also to many other types of turbulent-free surface flow problems (e.g., river flows, mold filling).

This book is based largely on the author's teaching and research during the last 14 years. The relevant postgraduate courses include Coastal Engineering and Offshore Hydrodynamics developed at National University of Singapore and Advanced Turbulence Modeling developed at Sichuan University. The relevant research is the modeling of water waves and turbulent-free surface flows at Cornell University, Hong Kong Polytechnic University, National University of Singapore, and Sichuan University. The intended readers of this book include students, researchers, and professionals. The main purpose of this book is twofold: (1) to introduce readers to the basic wave theories and wave models so that readers are able to choose appropriate existing models for different physical problems and (2) to provide adequate details of numerical techniques so that advanced readers can construct their own wave models and test the models against the benchmark tests provided.

This book is organized in the following way. The general background of water waves and water wave modeling is introduced in Chapter 1 and the basic hydrodynamics including turbulence modeling is reviewed in Chapter 2. In Chapter 3, the linear and nonlinear water wave theories based on potential flow assumption are discussed, followed by the introduction of various wave phenomena in oceans. In Chapter 4, different numerical methods are introduced and compared. Readers will be exposed not only the classical numerical methods (e.g., finite difference method, finite element method, and boundary element method), but also the innovative methods (e.g., meshless method, lattice Boltzmann method). Various types of water wave models based on different wave theories and solved by different numerical methods are introduced in Chapters 5. Extensive working examples and benchmark tests are provided to demonstrate the capability of these models. The modeling of wave–structure interaction, which is of primary interest to coastal and offshore engineers, is continued in Chapter 6, again with model demonstration and benchmark tests. The summary for the suitability of different wave models for different wave problems is provided in Chapter 7. In the same chapter, some related subjects that are not adequately covered elsewhere in the book are briefly introduced and the future trend of water wave modeling is highlighted.

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1 Introduction to water wave modeling

1.1 Introduction to waves

Waves are a common phenomenon in nature. By general definition, a wave is a movement with a certain periodic back-and-forth and/or up-and-down motion. A wave can also be defined as a disturbance that spreads in matter or space, obeying a certain "wave equation." Among the many types of waves, those that we are familiar with are sound waves, light waves, radio waves, and water surface waves. Although light waves and radio waves belong to electromagnetic waves that can travel in a vacuum, other types of waves need a medium to transmit the disturbance.

Waves that propagate through media, depending on the form of wave transmission, may be divided into two major categories, namely body waves and surface waves. In the case of body waves, they can travel in a single medium. A typical example is sound waves, which are caused by a pressure disturbance in a solid, liquid, or gas. Wave propagation is accomplished by the consecutive compression and dilatation that occur in the wave propagation direction. Another example of such a wave is the P-type seismic wave. Besides the above pressure-induced body waves, there are also stress-induced body waves, in which the medium moves in a direction perpendicular to the direction of wave propagation, for example, S-type seismic waves.

Surface waves always appear on the interface of two different media. The restoring force, which attempts to restore the interface to the equilibrium state, plays a predominant role in wave propagation. Surface waves can occur at the interface between a solid and a fluid, e.g., Rayleigh-type seismic waves. They can also occur at a fluid–fluid interface, e.g., ocean internal waves between two fluid layers with different density and ocean surface waves on an air–water interface.

1.2 Ocean surface waves and the relevance to engineering applications

In this book, we shall mainly focus on ocean surface waves. Ocean surface waves, or more generally surface water waves or simply water waves, are mainly generated by wind in deep oceans. Other possible sources of wave generation include astronomical attraction forces (e.g., tide), seismic disruptions (e.g., tsunami), underwater explosions, and volcano eruptions. Like all other surface waves, ocean surface waves require restoring forces to propagate. On most occasions, the gravity of Earth is the major restoring force. It is only when the scale of the wave is very small [i.e., O(1 mm)], that surface tension becomes the main restoring force for the resulting capillary wave.

Water waves share many similarities with light waves. For example, water waves experience refraction when they propagate over a changing bathymetry, similar to light traveling from one medium to another medium. Water waves form a certain diffraction pattern behind a large object or through a narrow gap. This is again similar to what light experiences under a similar condition. In fact, many theories established in optics, linear or nonlinear, can easily find their counterparts in water wave theories. The only exception is probably the wave-breaking phenomenon, which is an important physical process for water waves to dissipate excessive energy in terms of turbulence, but a similar process is not identified for light.

The study of water waves has important applications in engineering design. In deep oceans and deepwater offshore regions, wave height and wave period are two major design criteria. The practical problems include the maneuvering of ships against waves, the safe operation of offshore structures such as floating production storage offloading (FPSO) vessels or floating airports or terminals in extreme waves, and the stability of offshore structures such as bottom-mounted jacket platforms subjected to wave attacks. Because water depth is usually larger than wave length, the main wave mechanism to be considered in design is wave diffraction. The calculation of six-degree-of-freedom (DOF) structure motions, i.e., sway, surge, heave, pitch, roll, and yaw, and the control of the motion are the key considerations in the design. Other related problems are liquid sloshing in a tank induced by different external excitations and the "green water" effect caused by large-amplitude waves impinging on ship decks or offshore platforms.

In nearshore regions, waves can go through complex transformations with the combination of wave shoaling, wave refraction, wave diffraction, and wave breaking. There is also an active nonlinear energy transfer among different wave harmonics when waves propagate over abruptly changed bottom topography. Because of this, it is more challenging to understand wave motions in shallow water than in deep water. The engineering concerns for water waves in nearshore regions are quite different from those in deep seas. The functional performance of various coastal protections, which range from breakwater and groin to seawall and revetment, is one of the most important considerations in coastal engineering. Most of these protections are designed to provide a calm or at least reduced wave environment in the protected areas such as harbors or beaches.

1.3 Wave modeling

There are various types of techniques for modeling a prototype wave system, i.e., analytical wave modeling, empirical wave modeling, physical wave modeling, and numerical wave modeling. With their inherent advantages and limitations, these techniques shall be applied for different purposes.

1.3.1 Analytical wave modeling

A physical wave system in nature can be very complicated. We may find a way to represent the wave system by analyzing the system with a simplified theoretical model that should be able to capture the most important characteristics of the wave system. The model is usually expressed by mathematical equations, which are in the form of partial differential equations (PDEs) or ordinary differential equations (ODEs) governing the space–time relationship of the important variables for the waves. A good theoretical model is always constructed on rigorous mathematical derivations, each step of which has clear physical and mathematical assumptions and implications. When the equations are solved analytically for a specific condition, the closed-form solution can be obtained and used to predict wave system behavior accurately. This procedure of solution seeking is called analytical wave modeling, which is a powerful tool for us to understand the physical phenomenon of a particular wave system. One typical example of this kind of modeling is the study of the fission and fusion of solitons by solving the KdV nonlinear wave equation using inverse scattering transform. Another example is the wave-scattering pattern around a large vertical circular cylinder with the use of diffraction theory. Unfortunately, although most of the wave systems can be formulated theoretically, only very few of them can be solved analytically. This greatly limits the application of this approach to general wave problems.

1.3.2 Empirical wave modeling

An empirical formula is usually a simple mathematical expression summarized from available field data of a prototype system. It can describe the system behavior in terms of simple algebraic equations with important parameters. Since the empirical approach is simple and easy to implement, it is widely adopted in engineering design. In empirical wave modeling, empirical formulas can be used to estimate the maximum wave load on a structure (i.e., the Morison equation), the reflection coefficient from a certain type of structure, the maximum wave run-up on a beach, and the maximum wave overtopping rate over a dike. However, since empirical formulas are established on the known problems and database, when a new prototype system is considered, the existing empirical formulas may not be suitable.

1.3.3 Physical wave modeling

To understand a prototype wave system in nature, we can alternatively build a small-scale physical model in the laboratory as the miniature of the prototype. The wave characteristics (and wave loads on the model structure if wave–structure interaction is investigated) can be obtained by laboratory measurements. The information can then be extrapolated based on certain scaling laws to estimate what will really happen to the prototype system. This approach is called physical wave modeling. It is straightforward and allows us to visualize and understand the important physical processes from the small-scale model study. Typical examples of physical wave modeling include the studies of wave loads on an offshore structure, wave transmission and reflection from a breakwater, etc. However, when a physical system becomes very complicated, a physical model that satisfies all the important scaling laws, on which the physical model is designed and constructed, may not exist. Other approaches may have to be sought under such circumstances or when a physical model study is too expensive and time-consuming. Readers are referred to Hughes (1993) for a more detailed description of the physical models in coastal engineering and to Chakrabarti (1994) for offshore structure modeling.

1.3.4 Numerical wave modeling

A numerical wave model is the combination of the mathematical representation of a physical wave problem and the numerical approximation of the mathematical equations. Compared to theoretical modeling, the difference is only in the means of finding the solution of the governing equations for the wave problems. To model ocean waves numerically, we must start from some existing "wave equations" obtained from theoretical studies. In most cases, we can have more than one wave equation to describe the same wave phenomenon, depending on different levels of approximation made in the theoretical derivations. Similarly, the same wave model can also be applied to many different wave problems, as long as the basic assumptions in the model are valid.

1.4 Numerical models for water waves

In the following subsections, we will classify wave models based on their modeling capability so that readers can have a broad idea of the wave models that are available and the problems that they can solve. In Chapter 5, in addition to providing sufficient theoretical background of wave theories, we will further elaborate on the theoretical assumptions and capabilities of these wave models.

1.4.1 Wave spectral models

The most commonly employed wave model in modeling large-scale wave motion is the wave energy spectral model or wave action spectral model. This type of model is constructed on the assumption that a random sea state is composed of an infinite number of linear waves whose wave height is a function of wave frequency and the direction of wave propagation. For an individual wave train, the rate of change of wave energy (or action) flux is balanced by the wave energy transfer among different wave components in different directions (i.e., wave refraction) and different frequencies (i.e., nonlinear wave interaction) as well as energy input and dissipation. The representative wave energy spectral models are WAM (WAve prediction Model) (Hasselmann *et al.*, 1988) and WaveWatch III (Tolman, 1999), which can be used to model large-scale variations of wave heights in deep oceans. Being connected with an atmosphere model, a wave energy spectral model is able to predict global ocean wave climate. When the current effect is considered, the wave action spectral model can be formulated and used instead to simulate combined wave–current interaction in a large-scale nearshore region. The representation of such a model is SWAN (Simulating WAves Nearshore; Ris *et al.*, 1999).

With the wave phase information being filtered out in the formulation, the wave spectral model can use computational meshes much larger than a wavelength and thus can be applied in a very large area. Without wave phase information, however, the model is unable to represent wave diffraction that is phase-related. For this reason, this kind of model is usually used to provide far-field wave information only. The detailed wave pattern around coastal structures where diffraction is important is left to other types of wave models.

1.4.2 Mild-slope equation wave models

The mild-slope equation (MSE) was originally derived based on the assumptions of linear waves and slowly varying bottoms. The equation can be used to describe combined wave refraction and diffraction in both deep and shallow waters. In most events, the MSE model is employed to study monochromatic waves, though it can be applied to irregular waves by summing up different wave harmonics. The extension of the MSE to abruptly varying topography and larger amplitude waves was also attempted in the last two decades. So far, most of the applications of the MSE models are limited to the region from an offshore location to a nearshore location some distance away from the shoreline before wave nonlinearity becomes strong. One exception is its application in harbor resonance modeling because water depth in a harbor is usually deep even along the boundaries. The MSE has three different formulations, namely the hyperbolic MSE for a time-dependent wave field, the elliptic MSE for a steady-state wave field, and the parabolic MSE for a simplified steady-state wave field that has a primary wave propagation direction.

1.4.3 Boussinesq equation wave models

To model nearshore waves with strong wave nonlinearity, a Boussinesq equation wave model (or simply the Boussinesq model in water wave modeling) is often a good choice. The Boussinesq equations are depth-averaged equations with the dispersion terms partially representing the effect of vertical fluid acceleration. Rigorously speaking, Boussinesq equations are valid only from intermediate water depth to shallow water before the waves break. However, in engineering applications, the equations are often extended beyond the breaking point, up to wave run-up in the swash zone. This is possible by adding an artificial energy dissipation term for wave breaking. Besides, efforts are also made to extend the model to deeper water. Unlike the wave spectral model and the MSE model, the Boussinesq model does not have the presumption that the flow is periodic. Therefore, it can be applied to waves induced by impulsive motions, i.e., solitary waves, landslide-induced waves, tsunami, and unsteady undulation in open channels.

1.4.4 Shallow-water equation wave models

To model tsunami or other long waves (e.g., tides), a shallow-water equation (SWE) model is more likely to be adopted. Compared with the Boussinesq model, the SWE model is simpler because the flow is assumed to be uniform across the water depth and the wave-dispersive effect is neglected. The SWE model has a wide application range in modeling tsunami, tides, storm surges, and river flows. The main limitation of the SWE model is that it is suitable only for flows whose horizontal scale is much larger than vertical scale.

1.4.5 Quasi-three-dimensional hydrostatic pressure wave models

All the earlier discussed wave models can be operated on a horizontally two-dimensional (2D) plane due to vertical integration. When a shallow-water flow is modeled, the depth-varying information may still be needed on some occasions. A typical example is ocean circulation where the horizontal length scale is much larger than the vertical scale, but the vertical circulation, though relatively weak, is still of interest in many events. Thus, in this case, a three-dimensional (3D) model would be necessary. This type of model often solves the 3D Navier–Stokes equations (NSEs) directly under the hydrostatic pressure assumption. Under such an assumption, the solution procedure to the 3D NSEs is greatly simplified and the model is referred to as the quasi-3D model, against the fully 3D model to be discussed later. The model of this type is often solved in the σ-coordinate that maps the irregular physical domain to the regular computational domain for the ease of application of the boundary condition. The representative model of this kind is the Princeton Ocean model (POM).

1.4.6 *Fully three-dimensional wave models with turbulence: Navier–Stokes equation models*

To model fully 3D wave problems, we must turn to the general governing equations, NSEs, without a hydrostatic pressure assumption. The NSEs are derived from the general principle of mass and momentum conservation that is able to describe any type of fluid flow including water waves. With the inclusion of a proper turbulence model, it is possible for an NSE model to simulate difficult wave problems, e.g., nonbreaking or breaking waves, wave–current interactions, and wave–structure interactions. When breaking waves are simulated, there is the potential to include air entrainment on the surface of the water; when the wave–body interaction is computed, it can treat both the rigid body and the flexible body. With almost no theoretical limitation, this type of model seems to be the best choice of all. However, the main barrier that prevents the wide application of such a model is the expensive computational effort. To solve the fully 3D NSEs, the computation can be much more expensive than all the previously introduced wave models. So far, the application of such models in engineering computation is still restricted to the simulation of local wave phenomena near the location of interest, e.g., the surf zone when the breaking wave and/or sediment transport is considered and the flows around coastal and offshore structure when the wave–structure interaction is considered.

1.4.7 *Fully three-dimensional wave models without turbulence: potential flow models*

When turbulence is negligible and the bottom boundary layer thickness is thin (e.g., nonbreaking waves), the NSEs can be reduced to the Laplace equation based on potential flow theory. The theory is applicable to most of the linear and nonlinear nonbreaking waves and their interaction with large bodies. The Laplace equation can be solved numerically by many different methods. One of the most commonly used methods is the boundary element method (BEM), which converts domain integration into surface integration with the use of Green's theorem. This type of model is capable of simulating highly nonlinear waves in both deep and shallow waters. It is effective in the study of nonlinear wave transformation over changing topography, linear wave diffraction over a large body, and wave force on a large structure. The major limitation of such a model lies on the potential flow assumption that requires the flow to be irrotational. For this reason, the model is unable to simulate breaking waves as well as wave interaction with small bodies, during which the flow becomes rotational. Furthermore, the computational cost for modeling 3D fully nonlinear waves using BEM is rather high.

1.5 Books on water waves

There are many books on water waves. While some of these books address the general aspects of water wave theories (e.g., Stoker, 1957; Whitham, 1974; Newman, 1977; Lighthill, 1978; Mei, 1989; Dean and Dalrymple, 1991; Dingemans, 1997), other books address either specialized topics related to water waves (e.g., Le Méhauté and Wang, 1996) or the engineering applications in coastal and offshore engineering (Chakrabarti, 1987; Goda, 2000; Kamphuis, 2000; Reeve *et al*., 2004; Mei *et al*., 2005). The books dedicated to the numerical modeling of water waves normally cover only a particular type of wave model, e.g., Massel (1993) for wave spectral models and Dyke (2007) for shallow sea models. Only recently, Tao (2005) published a book (in Chinese) on water wave simulations by different wave models. This book is intended to be a different addition to the available literature so that readers can develop a thorough understanding of various water wave theories on which different wave models are constructed and applied to different physical problems.

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