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Excerpt
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Introduction

1.1 Key concepts

- This book offers an *introduction* to observing, analysing and predicting ocean waves for university students and professional engineers and, of course, others who are interested. Understanding the text of the book requires some basic knowledge of physics (mechanics), mathematics (analytical integrals and partial differential equations) and statistics (probabilities).
- The book is structured from *observing* to *describing* to *modelling* ocean waves. It closes with a description of the physics and numerics of the freely available, open-source computer model SWAN for predicting waves in coastal waters.
- Ocean waves (or rather: wind-generated surface gravity waves) can be described at several *spatial* scales, ranging from hundreds of metres or less to thousands of kilometres or more and at several *time* scales, ranging from seconds (i.e., one wave period) to thousands of years (wave climate).
  - (a) On *small* space and time scales (less than a dozen wave lengths or periods, e.g., the surf zone at the beach or a flume in a hydraulic laboratory), it is possible to describe the actual sea-surface motion in detail. This is called the phase-*resolving* approach.
  - (b) On *intermediate* space and time scales (from dozens to hundreds of wave lengths or periods, e.g., a few kilometres or half an hour at sea), the wave conditions are described with average characteristics, the most important of which is the wave spectrum. This requires the wave conditions to be constant in a statistical sense (stationary and homogeneous).
  - (c) On *large* space and time scales (from hundreds to hundreds of thousands of wave lengths or periods, e.g., oceans or shelf seas), space and time should be divided into segments, with the waves in each described with one spectrum. The sequence of segments allows the spectrum to be treated as varying in space and time.
  - (d) On a *climatological* time scale (dozens of years or more), usually only the statistical properties of a characteristic wave height (the significant wave height) are considered.

1.2 This book and its reader

Waves at the surface of the ocean are among the most impressive sights that Nature can offer, ranging from the chaotic motions in a violent hurricane to the tranquillity of a gentle swell on a tropical beach. Everyone will appreciate this poetic aspect but scientists and engineers have an additional, professional interest. The scientist is interested in the dynamics and kinematics of the waves: how they are generated by the wind, why they break and how they interact with currents and the sea bottom. The engineer (variously denoted as ocean engineer, naval architect, civil engineer, hydraulic engineer, etc.) often has to design, operate or manage structures or natural systems in the marine environment such as offshore platforms, ships, dykes, beaches and tidal basins. To a greater or lesser extent, the behaviour of such structures and systems is affected by the waves and some basic knowledge of these waves is therefore required. This book offers an *introduction* to this fascinating subject for engineers and university students, particularly those who need to operate numerical wave models. Others may be interested too, if only out of pure curiosity.

The book starts where anyone interested in ocean waves should start: with observing waves as they appear in Nature, either in the open sea or along the shore.[1] Take the opportunity to go out to sea or wander along the shores of the ocean to experience the beauty and the cruelty of waves, and to question the 'where and why' of these waves. The book therefore starts with *observation* techniques, before continuing with the question of how to describe these seemingly random motions of the sea, which we call waves. Only then does the book present a truly theoretical concept. It is the variance density spectrum of the waves that is used to *describe* the waves. This, in its turn, is followed by the linear *theory* of surface gravity waves (as they are formally called). This theory gives the interrelation amongst such physical characteristics as the surface motion, the wave-induced pressure in the water and the motion of water particles. It beautifully supplements the concept of the spectrum. Initially, the book treats only open-water aspects of the linear wave theory, in other words, deep-water conditions without currents or a coast. This provides, together with the spectral description of the waves, an introduction to the energy balance of waves in oceanic waters. Sources and sinks are added to this balance, to represent the generation (by wind), the interaction amongst the waves themselves (wave–wave interactions) and the dissipation of the waves (by white-capping). Although several theories for these processes have been developed, the actual formulations in numerical wave models are still very much empirical and therefore relatively simple and descriptive. I will use these model formulations so that the reader will quickly become familiar with the basic ideas and results of these theories. This will satisfy many students of waves in oceanic waters. For those interested in waves in coastal waters, the book proceeds by adding the effects of sea-bottom topography, currents and a coast (shoaling, refraction, diffraction and reflection). The corresponding formulations of the generation, wave–wave interactions and dissipation in coastal waters are more diverse and empirical than those for oceanic waters and the presentation is consequently even more descriptive.

The text of the book provides an insight into basic theories and practical results, which will enable the reader to assess the importance of these in his or her field of engineering, be it coastal engineering, ocean engineering, offshore engineering or naval architecture. I have tried to balance the presentation of the material in a manner that will, I hope, be attractive to the practical engineer rather than the theoretically

[1] Reading a brief history of wave research may also be interesting (e.g., Phillips, 1981; Tucker and Pitt, 2001).

minded scientist. I am well aware that some basic knowledge that is required to understand certain parts of the text has sunken deep into the recesses of the reader's memory (statistics is a notorious example). In such cases, the required information is briefly reviewed in separate notes and appendices, which are intended as prompts rather than as true introductions. I hope that the scientifically minded reader may find the book sufficiently intriguing that it will lead him to more fundamental and advanced books (for instance Geernaert and Plant, 1990; Goda, 2000; Janssen, 2004; Komen *et al*., 1994; Lavrenov, 2003; LeBlond and Mysak, 1978; Phillips, 1977; Sawaragi, 1995; Svendsen, 2006; and Young, 1999).

1.3 Physical aspects and scales

If the word 'waves'[2] is taken to mean 'vertical motions of the ocean surface',[3] then wind-generated gravity waves are only one type amongst a variety that occur in the oceans and along the shores of the world. All these waves can be ordered in terms of their period or wave length (see Fig. 1.1). The longest waves are *trans-tidal waves*, which are generated by low-frequency fluctuations in the Earth's crust and atmosphere. *Tides*, which are slightly shorter waves, are generated by the interaction between the oceans on the one hand and the Moon and the Sun on the other. Their periods range from a few hours to somewhat more than a day and their wave lengths accordingly vary between a few hundred and a few thousand kilometres. This is (very) roughly the scale of ocean basins such as the Pacific Ocean and the Northern Atlantic Ocean and of shelf seas such as the North Sea and the Gulf of Mexico. Although tides may be called waves, they should not be confused with 'tidal waves', which is actually a misnomer for tsunamis (see below).

The wave length and period of *storm surges* are generally slightly shorter than those of tides. A storm surge is the large-scale elevation of the ocean surface in a severe storm, generated by the (low) atmospheric pressure and the high wind speeds in the storm. The space and time scales of a storm surge are therefore roughly equal to those of the generating storm (typically a few hundred kilometres and one or two days). When a storm surge approaches the coast, the water piles up and may cause severe flooding (e.g., the flooding of New Orleans by hurricane Katrina in August of 2005, or the annual flooding of Bangladesh by

[2] Waves are basically disturbances of the equilibrium state in any given body of material, which propagate through that body over distances and times much larger than the characteristic wave lengths and periods of the disturbances.

[3] Waves *beneath* the ocean surface, for instance at the interface between two layers of water with different densities, are called 'internal waves'. They will not be considered in this book.

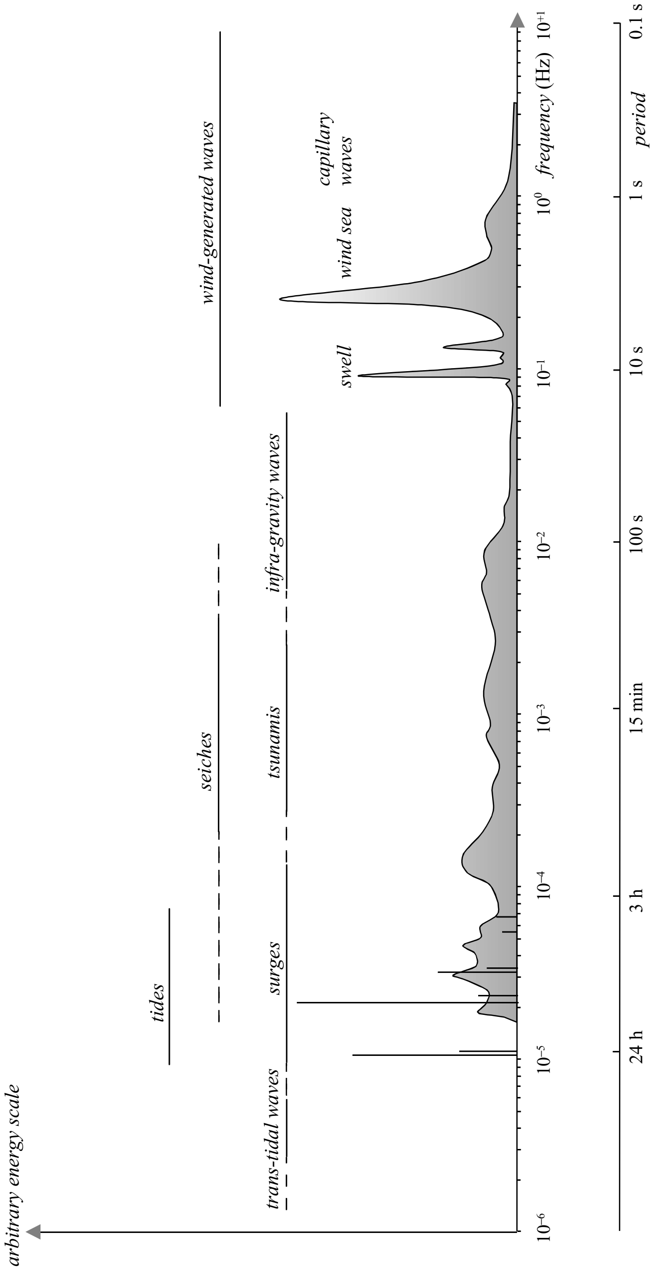

Figure 1.1 Frequencies and periods of the vertical motions of the ocean surface (after Munk, 1950).

cyclones[4]). The next, somewhat smaller scale of waves is that of *tsunamis*. These are waves that are generated by a submarine 'land' slide or earthquake. They have a bad reputation, since they are difficult to predict and barely noticeable in the open ocean (due to their low amplitude there) but they wreak havoc on unsuspecting coastal regions as they increase their amplitude considerably on approaching the coast (the Christmas tsunami of 2004 in the Indian Ocean being the worst in living memory). The waves at the next scale are even more difficult to predict. These are standing waves, called *seiches*, with a frequency equal to the resonance frequency of the basin in which they occur (in harbours and bays or even at sea, for instance in the Adriatic Sea). In a harbour, the amplitude of a seiche may be large enough (1 m is no exception) to flood low-lying areas of the harbour, break anchor lines and otherwise disrupt harbour activities. These waves are usually generated by waves from the open sea, the source of which is not well understood (although some, at least, are generated by storms). Next is the scale of *infra-gravity waves*. These waves are generated by groups of wind-generated waves, for instance in the surf zone at the beach, where these waves are called surf beat, with periods of typically a few minutes. The period of the next category, *wind-generated waves*, is shorter than 30 s. When dominated by gravity (periods longer than 1/4 s), they are called *surface gravity waves* (the subject of this book). While they are being generated by the local wind, they are irregular and short-crested, and called *wind sea*. When they leave the generation area, they take on a regular and long-crested appearance and are called *swell* (the beautiful swell on a tropical beach is generated in a distant storm). Waves with periods shorter than 1/4 s (wave lengths shorter than about 10 cm), are affected by surface tension and are called *capillary waves*.

The above types of waves are defined in terms of their wave period or wave length. Wind-generated surface gravity waves are thus characterised by their period of 1/4–30 s and corresponding wave length of 0.1–1500 m (in deep water). For describing the variation in space and time of *these* waves, other scales are used: the scales at which the processes of their generation, propagation and dissipation take place.

(1) On small scales, of the order of a *dozen or fewer* wave periods or wave lengths (however loosely defined), in other words, dimensions of about 10–100 s and 10–1000 m in real life (e.g., the dimension of the surf zone or a small harbour), waves can be described in great detail with theoretical models (details down to small fractions of the period or wave length). In these models, the basic hydrodynamic laws can be used to estimate

[4] Hurricanes occur in many parts of the world under different names. For the Atlantic Ocean and the eastern Pacific Ocean the term *hurricane* is used, whereas for the western Pacific Ocean, the term *typhoon* is used. In the Indian Ocean the term *cyclone* is used. A *tornado* is something entirely different. It denotes the much smaller atmospheric phenomenon of a relatively small but severe whirlwind (a diameter of a few hundred metres or less, whereas the scale of a hurricane is hundreds of kilometres with an eye of about 25 km) with a vertical axis extending from the clouds to the ground, usually occurring in thunderstorms, with much higher wind speeds and a much lower atmospheric pressure in the centre than in hurricanes.

the motion of the water surface, the velocity of the water particles and the wave-induced pressure in the water at any time and place in the water body, e.g., to compute the impact of a breaking wave on an offshore structure. Nothing in these models is left to chance; the Newtonian laws of mechanics control everything. In other words, in this approach the description and modelling of the waves are fully deterministic. Rapid variations in the evolution of the waves can be computed, e.g., waves breaking in the surf zone at the beach. Since this approach provides details with a resolution that is a small fraction of the wave length or period, it is called the *phase-resolving* approach.

(2) On a somewhat larger scale, of the order of a *hundred* wave periods or wave lengths, in other words, dimensions of about 100–1000 s and 100–10 000 m in real life, the above phase-resolving approach is not used. The reasons are as follows:
   (a) the sheer amount of numbers needed to describe the waves would be overwhelming;
   (b) details of the wind that generates the waves cannot be predicted at this scale and therefore the corresponding details of the waves cannot be predicted either;
   (c) even if such details could be observed or calculated, they would be incidental to that particular observation or calculation and not relevant for any predicted situation; and
   (d) the engineer does not require such details at this scale.

   The description of ocean waves at this scale need therefore not be aimed at such details. Rather, such details should be ignored and the description should be aimed at characteristics that are relevant and predictable. This can be achieved by taking certain averages of the waves in space and time. This is the *phase-averaging* approach, in which statistical properties of the waves are defined and modelled. Meaningful averaging requires that, in some sense, the wave situation is constant within the averaging interval, i.e., the situation should be *homogeneous and stationary* in the space and time interval considered. If the waves are not too steep and the water is not too shallow, the physically and statistically most meaningful phase-averaged characteristic of the waves is the *wave spectrum*. This spectrum is based on the notion that the profile of ocean waves can be seen as the superposition of very many propagating harmonic waves, each with its own amplitude, frequency, wave length, direction and phase (the random-phase/amplitude model).

(3) Next are the three scales of coastal waters (of the order of *one* thousand wave lengths and periods), shelf seas (of the order of *ten* thousand wave lengths and periods) and oceans (of the order of a *hundred* thousand wave lengths and periods). In oceans and shelf seas, the time and space scales are generally determined by the travel time of the waves through the region, the spatial scale of the region itself and the scales of the wind and tides. In coastal waters, the space scale is also determined by coastal features such as beaches, bays and intricate topographical systems, such as tidal basins with barrier islands, channels and flats. For instance, a string of barrier islands may be 50–100 km long with a tidal basin behind it that is 10–20 km wide. The travel time to the mainland behind the islands is then typically only 15–30 min. In shelf seas and oceans, the space scale is determined by the size of the basin itself and by the space

scale of the weather systems. For instance, the North Sea is roughly 500 km wide and 1500 km long, while the weather systems there are only slightly smaller. The travel time across the North Sea for waves with period 10 s is typically 24 h, which is of the same order as the time scale of the storms there. The scale of the Pacific Ocean is roughly 10 000 km, and a 20-s swell takes about a week to travel that distance. All these scales are too large to use only *one* spectrum to characterise the waves. Instead, the spectrum under these conditions is seen as a function that varies in space and time. It can be forecast with numerical wave models, accounting for the generation, propagation and dissipation of the waves. The spectrum is thus determined in a *deterministic* manner from winds, tides and seabed topography. Note that we thus compute statistical characteristics of the waves (represented by the spectrum) in a deterministic manner.

(4) On a time scale of *dozens of years (or more)* the wave conditions can be characterised with long-term statistics (called wave climate) obtained from long-term wave observations or computer simulations. Acquiring a wave climate is basically limited to sorting and extrapolating a large number of such observations or simulations.

In summary: ocean waves are generally not observed and modelled in all their detail as they propagate across the ocean, into shelf seas and finally into coastal waters. Such details are generally not required and they are certainly beyond our capacity to observe and compute (except on a very small scale). The alternative is to consider the statistical characteristics of the waves. In advanced techniques of observing and modelling, these statistical characteristics are represented by the wave spectrum, which can be determined either from observations or with computer simulations based on wind, tides and seabed topography.

1.4 The structure of the book

The structure of the book follows roughly the above sequence of the various aspects of ocean waves, i.e., from *observing* ocean waves with instruments to *predicting* waves with computer models:

CHAPTER 1 INTRODUCTION
The present, brief characterisation of this book and its contents.

CHAPTER 2 OBSERVATION TECHNIQUES
The phenomenon of ocean waves is introduced by describing techniques to observe waves with *in situ* instruments or *remote-sensing* instruments. *In situ* instruments float on the ocean surface (buoys and ships), pierce the water surface (e.g., wave poles) or are mounted under water (e.g., pressure transducers). Remote-sensing

instruments, with their lenses or antennas, are usually located high above the oceans (e.g., laser or radar in airplanes and satellites).

CHAPTER 3 DESCRIPTION OF OCEAN WAVES

Having introduced the techniques used to observe the apparent chaos of ocean waves in the previous chapter, the techniques to describe this phenomenon are introduced. The basic concept for this is the *random-phase/amplitude* model. It leads to the definition of the variance density *spectrum*. Interpreted as the energy density spectrum, this spectrum provides the basis for modelling the physical aspects of the waves.

CHAPTER 4 STATISTICS

All *short-term* statistical characteristics of the waves can be expressed in terms of the spectrum (within the linear approach of the random-phase/amplitude model). Here, 'short-term' should be interpreted as the time during which the wave condition is, statistically speaking, stationary. This property of the spectrum is exploited to estimate, theoretically, important statistical parameters such as the significant wave height and the maximum individual wave height within a given duration (e.g., a storm). *Long-term* wave statistics can be arrived at only by collecting observations or by computing many wave conditions from archived wind data. Extrapolating such long-term statistical information to estimate extreme conditions, for instance to determine design conditions of an offshore structure, was, until recently, more an empirical art than a well-founded science.

CHAPTER 5 LINEAR WAVE THEORY (OCEANIC WATERS)

The linear theory of surface gravity waves is the basis for deriving the physical characteristics of wind-generated waves. This linear approach beautifully supplements the concept of the wave spectrum which assumes linear waves. The theory, as treated in this chapter for oceanic waters, addresses only local characteristics such as wave-induced orbital motions, wave-induced pressure fluctuations in the water and wave energy, together with such aspects as phase velocity and the propagation of wave energy. Only the simplest conditions are considered: the water has a constant depth, there are no obstacles, currents or coastlines and the wave amplitude is constant in space and time. The theory, being linear, ignores the effect of wind, dissipation and other nonlinear effects (these are treated in Chapters 6 and 8).

CHAPTER 6 WAVES IN OCEANIC WATERS

The concept of the wave spectrum, combined with the linear wave theory for oceanic waters, is the basis for describing the propagation of the waves on an oceanic scale with the spectral energy balance. Obviously, such modelling requires additional information on the generation of the waves (by wind), their dissipation (by white-capping) and other nonlinear effects (quadruplet wave–wave interactions).

CHAPTER 7 LINEAR WAVE THEORY (COASTAL WATERS)

In this chapter, the linear wave theory is continued for the more complex conditions of coastal waters with variable water depth, currents, obstacles, coastlines and rapidly varying wave amplitudes (compared with oceanic conditions). The corresponding phenomena of shoaling, refraction, diffraction, reflection, radiation stresses and wave-induced set-up are introduced.

CHAPTER 8 WAVES IN COASTAL WATERS

The modelling of waves in coastal waters, including the surf zone, is considerably more challenging than that in oceanic waters, not only because the propagation of the waves is more complicated, but also because the processes of generation, dissipation and nonlinear wave–wave interactions increase in number and complexity. The processes that dominate in oceanic waters are slightly modified in coastal waters but, more importantly, the processes of bottom friction, surf-breaking and triad wave–wave interactions are added.

CHAPTER 9 THE SWAN WAVE MODEL

To illustrate one application of the concepts and theories that are presented in this book, and to provide SWAN users with background information, the formulations and techniques of the third-generation SWAN model for waves in coastal waters are given in this final chapter.

2

Observation techniques

2.1 Key concepts

- *Visual* observations are often the only source of wave information available to the engineer. Sometimes measurements made with *instruments* are available.
- Measurement techniques can be divided into *in situ* techniques (instruments deployed in the water) and *remote-sensing* techniques (instruments deployed at some distance above the water).
- The most common *in situ* instruments are wave buoys and wave poles. Other *in situ* instruments are inverted echo-sounders, pressure transducers and current meters. These instruments need to be mounted on some structure at sea.
- The most common remote-sensing technique is radar, which is based on actively irradiating the sea surface with electro-magnetic energy and detecting the corresponding reflection. Radar may be deployed from the coast (e.g., with a receiving station in the dunes), from fixed platforms (e.g., oil-production platforms) or from moving platforms at relatively low altitude (airplanes) or high altitude (satellites).
- Radar can be used to obtain images of the sea surface, but it can also be used as a distance meter or as a surface-roughness meter.
- Each measurement technique has its own peculiarities as regards operational performance, accuracy, maintenance, cost and reliability.
- The most common result of a wave measurement is a time record of the sea-surface elevation at a fixed (horizontal) location.

2.2 Introduction

Waves are not only observed by surfers, swimmers or tourists from the beach. Experienced crew members onboard voluntary observing ships (VOS; or voluntary observing fleet, VOF), too, observe the waves and report wave height, period and direction daily to meteorological institutions around the world. Scientists and engineers too are watching waves. They want to quantify what they see; they want to record every detail of the moving sea surface to study and eventually predict waves. They therefore need to record the up-and-down motion of the surface, as a function of time (see Fig. 2.1), or as a function of horizontal co-ordinates (see Fig. 2.2).

Such detail is not available in *visual* observations but visual observations of the *height* of waves are fairly reliable if carried out by experienced observers who follow specific instructions (this is not true for the wave period) but they have their own peculiarities. For instance, ships try to avoid heavy weather and storms