Introduction

In this section, the matter of the problem and general views are discussed. We highlight the facts that made people realize that there was a problem, and discuss the main questions surrounding the phenomenon of rogue waves.

> "Our captain, who has 20 years on the job, said he never saw anything like it."
> — Susan Robison, Norwegian Cruise Line spokeswoman, New York Daily News, April 17, 2005

There are a number of well-documented cases of the occurrence of unexpectedly large waves; some of them are described in Chap. 1, and other descriptions may be found in references therein. It is well understood that the sea may be dangerous for sailing. It is also generally recognized that the modern level of engineering is high and can generally protect people from many disasters. But where does the problem lie? People are accustomed to thinking that the construction and technical equipment of modern ships can allow safe sailing everywhere on the ocean. This confidence might be true if we had a full and realistic comprehension of all the possible dynamics on the sea surface, but this is not true.

The first vital question arises about the possible maximum wave heights on the sea surface generated by the wind. The wave height H is defined as the vertical distance between the wave crest and the deepest trough preceding or following the crest (see Fig. I.1, and (Massel 1996) for details).

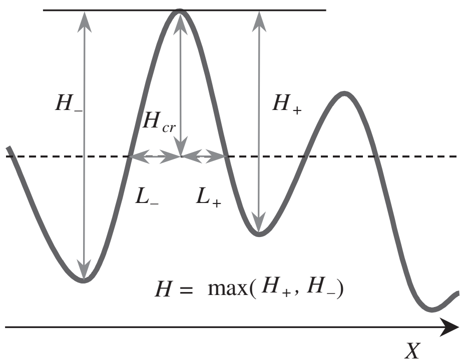

Fig. I.1 A cross section of a sea surface wave profile propagating in X direction

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When Captain Dumont d'Urville, a French scientist and naval officer in command of an expedition in 1826, reported encountering waves up to 30 meters height, he was openly ridiculed. Three of his colleagues supported his estimate but could not help him to be believed. Apparently the largest reported wave in the open sea reached a height of about 34 m (112 ft). The United States Ship (USS) Ramapo in the North Pacific reported it in 1933 (Draper 1964, Dennis and Wolff 1996). Crew members standing on the ship's bridge could measure the height of a wave by lining up its crest with the horizon and a point on the ship's mast (making the line of sight approximately horizontal) while the stern of the ship was at the bottom of a trough (see Fig. I.2).

Until now, the largest reliable instrumentally measured waves have had heights of 30 m; they were registered during the "Halloween Storm" in 1991 and Hurricane Luis in 1995. Waves with heights a little bit more than 29 m were measured under severe, but not exceptional, wind conditions in 2000 by a British oceanographic research vessel near Rockall, west of Scotland (Holliday et al. 2006). Liu and MacHutchon (2006) report higher waves, but they agree that some of them *must* be errors in the gauge, thus making the results suspect.

Nowadays, observations and measurements of high waves from space have become possible. A three-week registration of surface waves from the European satellite ERS-2 revealed regions with high waves (see Fig. I.3) and detected a wave of 29.8 m height. Bearing in mind that ships are often designed for 10–15 m wave heights, it becomes obvious that the observed waves are real threats that may cause damage and even the loss of ships (Faulkner 2001).

High waves are usually generated by storms and hurricanes; and rogue waves are obviously also much more probable during severe weather (Guedes Soares et al. 2004). Komar (2007) reports of a substantial increase in typical wave heights during a season of tropical storms and hurricanes in the North Atlantic. The rate of increase for one of the buoys used in the study is 5.4 cm per year, which has resulted in 1.8 m growth for the period of 1975–2005. The most likely explanation for that it is related to the progressive intensification of the hurricanes themselves.

Most of the casualties (about 60%) are related to operational causes (e.g., fire, collision, machinery damage), while the remaining 40% are characterized by design and maintenance causes (i.e., water ingress, hulls breaking into two pieces, and capsizing). In the case of marine structures (such as oil and gas platforms), the role of the design is even more important since a platform cannot tack, and meets

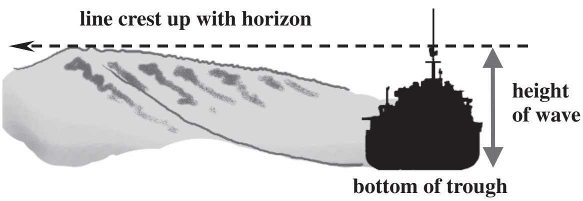

Fig. I.2 Observation of the highest reported wave by the crew members of the United States Ship "Ramapo" (Dennis and Wolff 1996)

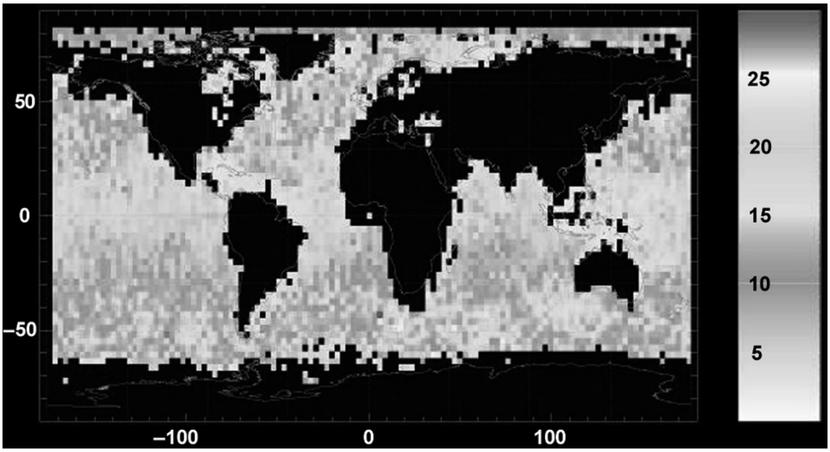

Fig. I.3 Map showing maximum single wave heights (in meters) derived from three weeks of ERS-2 SAR data acquired in August-September 1996. Reproduced from (Rosenthal et al. 2003)

a wave "as it is." Practical designs always involve compromises between safety and efficiency, and the goal is to account for expected events over the useful lifetime of a ship or structure. The crucial question that should be answered when estimating the danger is how often extreme events actually happen.

For example, the present Norwegian Petroleum Directorate's regulations describe that loads in the ultimate limit state and the serviceability limit state controls should be checked with an annual probability of 10^{-2} (once in 100 years). These waves may hit the deck structure, but they should not cause damage; the platform should be capable of full operation after an incident. The waves should not hit areas where people can be hurt. Imposing restrictions for personnel in certain areas can meet this last requirement. Loads in the accidental limit state control should meet an annual probability rate of 10^{-4} (once in 10,000 years). The total safety of the platform should not be jeopardized, personnel should have the possibility to be safely evacuated, and no major pollution should occur. Localized damage during a severe storm does not necessarily mean that a platform was poorly designed. Occasional damage might be repaired at a lower cost than building and installing a platform with a higher deck.

The current state of affairs, however, is obviously not acceptable. Casualties happen too frequently and are too dramatic. Hundreds of vessels sink and hundreds of people perish annually (see Fig. I.4), although the situation has taken a turn for the better over the last few years. The list of accidents related to the attacks of huge waves contains many recent dates. Twenty-two (22) super carriers were lost or severely damaged between 1969 and 1994 due to the occurrence of sudden rogue waves; a total of 542 lives were lost as a result (Lawton 2001). About 650 incidents are counted during the period from 1995 to 1999 due to bad weather, including total losses of all propelled sea-going merchant ships in the world weighing 100 gross tons or more (see Fig. I.5). Thirty-six percent (36%) of them foundered, 25% suffered water ingress, 6% incurred evere hull damage, and 8% capsized as intact ships (Toffoli et al. 2005).

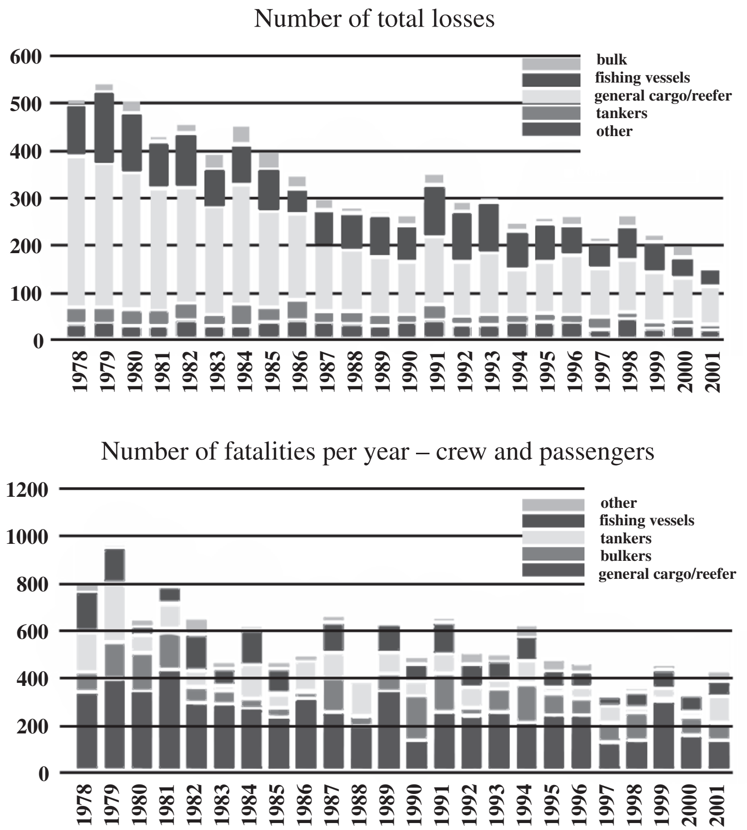

Fig. I.4 Number of total losses and number of fatalities per year of crew and passenger during 1978–2001 (Source: Det Norske Veritas, http://www.dnv.com/)

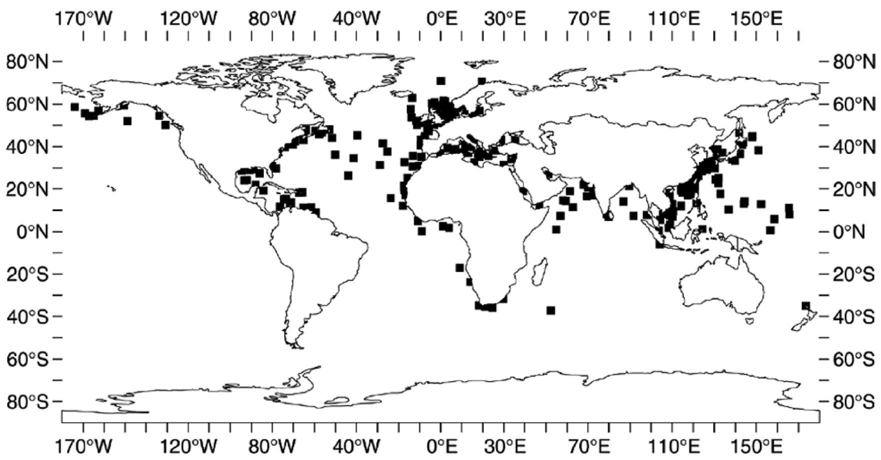

Fig. I.5 Distribution of shipping accidents from 1995–1999. (Toffoli et al. 2005, reproduced with permission from Elsevier)

Offshore platforms are also vulnerable to rogue waves. On 15 February 1982, a giant wave smashed the windows and flooded the control room in a drilling rig run by Mobil Oil on the Grand Banks of Newfoundland. Shortly afterwards the rig capsized and sank, killing all 84 people on board (Lawton 2001). The famous New Year Wave attacked the Draupner Jacket platform on 1 January 1995, with a height close to 26 m while the typical surrounding waves were about 11–12 m and the maximum expected wave height was estimated at about 20 meters (Karunakaran et al. 1997, Trulsen and Dysthe 1997).

The number of accidents reported by the mass media is growing, and the problem of huge sea waves has attracted many people's attention. Striking photos of damage collected in Fig. I.6 prove that those waves were really abnormal for the ship design of the time. Recent accidents with large passenger carriers (Queen Elizabeth 2 in 1995, Caledonia Star and Bremen in 2001, and Explorer, Voyager, and Norwegian Dawn in 2005) demonstrate the potential threat of rogue waves to normal people, while casualties with a subsequent pollution of large coastal areas (Erika in 1999, Prestige in 2002) show examples of indirect losses and the importance of safe navigation on a global scale.

So, the importance of the safe use of ocean stationary and drifting structures is obvious, as well as the message that current theoretical and engineering models underestimate the occurrence of extreme sea waves.

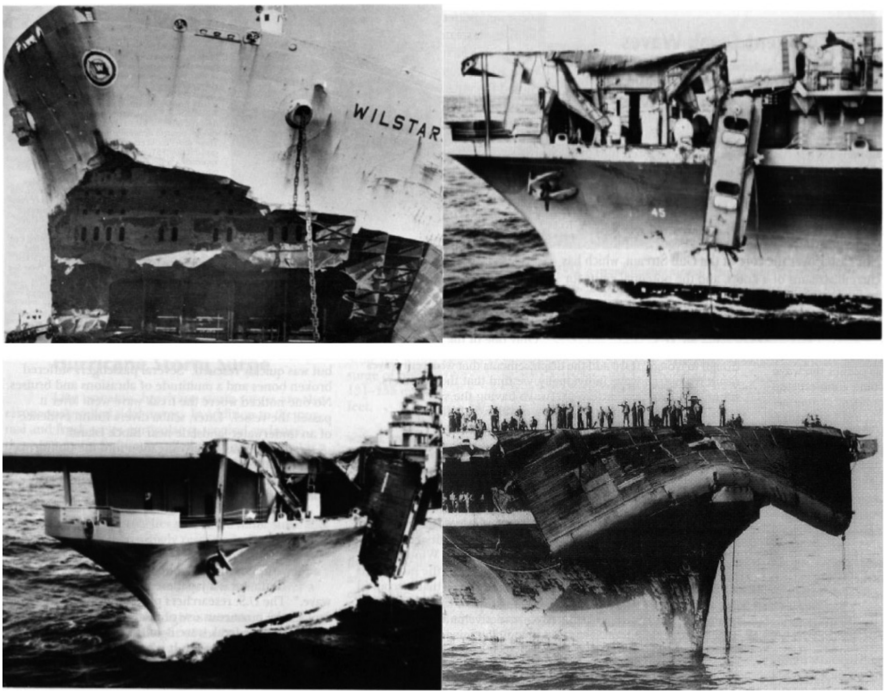

Fig. I.6 Photos of damage caused by huge waves (from Olagnon (2000))

Two different types of waves usually characterize the sea surface on a scale of a few meters to a few hundred meters. They are associated with wind above waves: wind waves and swells. Whereas the first refers to waves still under the influence of the wind, the latter refers to waves that have already moved out of the generating area or are no longer affected by the wind. The relatively frequent occurrence of freak wave events and the spreading of these accidents throughout the world's oceans (see Fig. I.7) allows us to believe that the freak wave phenomenon is related to the dynamics of typical waves on the sea surface—i.e., generated by the wind and more or less freely propagating.

The "wave age"[1] may be characterized by the distance (fetch) over which the wind blows over the sea surface. Various wave amplification mechanisms have been suggested by different authors (see Belcher and Hunt 1993). Due to the gravity force, the surface perturbations split into traveling waves. Qualitatively, the fully developed waves (with a long fetch, which needs large areas) depend on the wind speed only. According to dimensional analysis, the wave periods are then expressed as $T \sim U_w/g$, where U_w is the wind speed and $g = 9.8\,\text{m/s}^2$ is the gravity acceleration. Thus, the stronger the wind is, the longer the waves will be. The surface waves have periods of several seconds in weak wind, 8–10 s in moderate wind, and 20–30 s in very strong winds. Free gravity surface waves over the deep ocean have a phase speed of $C_{ph} = gT/(2\pi)$ (see details in Chap. 2), and therefore the wave lengths $\lambda = C_{ph}T$ vary from several meters up to several hundred meters. In comparison with wind seas, swells generally have longer periods and larger lengths.

Small-amplitude waves are almost sinusoidal, although large-amplitude waves are not symmetric due to nonlinear bound wave corrections. Because of this effect

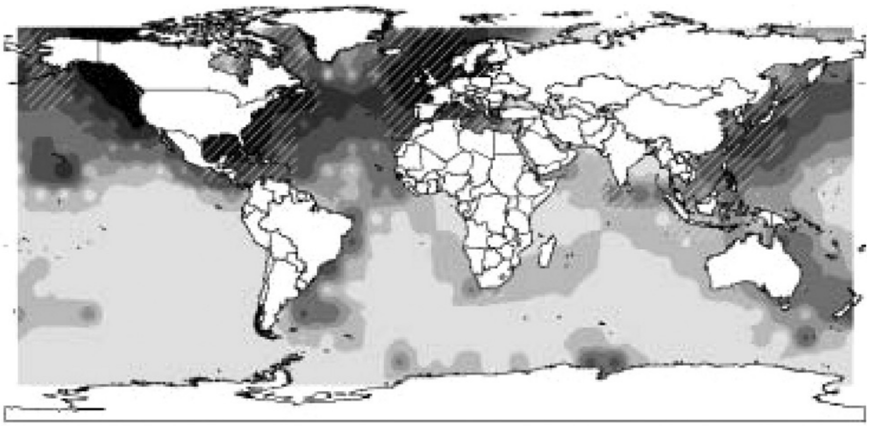

Fig. I.7 Global distribution of ship density (intensity of the gray color) and locations of accident occurrences (*hatched*). (Monbaliu and Toffoli 2003, reproduced with permission)

[1] More exactly, the wave age is defined as the ratio C_{ph}/U_{10} or C_{ph}/U_* where C_{ph} is the phase speed of water wave components at the spectral peak frequency and U_{10} and U_* are the wind velocity at height 10 m above the mean level and friction velocity respectively.

the crests become sharper, while troughs – smoother. Waves cannot be too high. Due to nonlinearity they break. In the open sea (when water depth much exceeds the wavelengths) the strength of nonlinearity is characterized by the wave steepness $s = KH/2$, where H is the wave height already introduced, and $K = 2\pi/\lambda$ is the wavenumber. In most cases, a regular plane wave (i.e., a wave that has a permanent profile in the crosswise direction) comes to the breaking onset when the steepness has a value of about $s \approx 0.4$. Thus, a 30 m breaking wave has a length of about 250 m and a period of about 12 s. These wave estimations look quite realistic.

The breaking phenomenon restricts the wave heights. Young waves are shorter than old ones. For short-fetch situations, growing waves are inhibited by breaking before they can grow very high. This view is supported by observations that typical waves do indeed tend to break in developing seas while smaller-scale waves tend to break in fully-developed seas. Rather large mean wave steepness is often reported in areas of relatively low significant wave height.

On the whole, the global wave climate indicates that high-wave activities are located at the highest/lowest latitudes (Fig. I.3). Ocean regions such as the North Pacific and the North Atlantic, the North Sea, the Gulf of Alaska, and the Bering Sea show the most severe sea states. However, the largest significant wave height does not occur necessarily where the largest wave steepness occurs. High steepness was reported close to the eastern coast of North America, the southern North Sea, the Mediterranean Sea, and the eastern coast of Asia, where the significant wave height was often lower than 3 m (Monbaliu and Toffoli 2003, Toffoli et al. 2005).

Relatively high waves are expected to be recorded during specific incidents. Toffoli et al. (2005) found, however, that rather low significant wave heights occurred during certain ship accidents that were reported as being due to bad weather. Thus, we are forced to come to the conclusion that wave height is not the only significant injurious factor that gives waves rogue status.

Indeed, the wave impact upon marine structures may be determined by other parameters, such as steepness, crest height (H_{cr}), and horizontal wave asymmetry (difference in L_+ and L_-) (see Fig. I.1), etc. Different types of ships may suffer from different wave parameters and conditions. Toffoli et al. (2005) note, for example, that fishing vessels have mainly capsized while fishing or loading fish. This is an important practical question that is not fully answered.

On the other hand, existing measurements and theories do not always allow a very detailed description of the accidents. Thus, a simplified definition of a freak wave becomes relevant. In this book, we employ the simple definition that a freak wave exceeds at least twice the significant wave height:

$$AI > 2, \quad \text{where} \quad AI = \frac{H_{fr}}{H_s}. \tag{I.1}$$

Here, H_{fr} is the height of the freak wave, and H_s is the significant wave height, which is the average wave height among one third of the highest waves in a time series (usually of length 10–30 min). In that way, the abnormality index (AI) is the only parameter defining whether the wave is rogue or not.

An alternative point of view exists that there are *rogue waves* that consist of two populations: (i) *"classical" extreme waves* (that are described by conventional physics, models and statistics) and (ii) *"freak" extreme waves* (that need new approaches and theories) (Haver 2005). This concept is based on probabilistic considerations. In this book, we are more interested in physical mechanisms and statistics of all kinds of extreme waves, thus we do not make such separation and consider all terms listed in the Preface (rogue, freak, etc. waves) to be synonyms and applicable to a wave if it agrees with condition (I.1). Doing a simple statistical analysis of the Reference Lists of this book, one can easily see that the word "rogue" may be found there most frequently, "freak" is less frequent, and "extreme" is at the bottom of this popularity rating. This may support (in part) the title of the book, where the term "rogue" is used instead of all others.

Hundreds of waves satisfying condition (I.1) have been recorded by now (see Chap. 1), and several waves with an abnormality index larger than three ($AI > 3$) are known. Theoretical predictions allow even higher rates of wave amplification. This is seemingly confirmed by the results of Liu and MacHutchon (2006); they hypothesize that "typical" rogue waves achieve amplification in the range of $2 < AI < 4$. Nevertheless, the variety of conditions when the waves were measured do not allow for rigorous statistical study of these waves—they still remain exceptional events.

There are a number of questions that arise and need to be answered—some of them are given here and many are the titles of recent scientific articles:

– Are there different kinds of rogue waves?
– Are rogue waves beyond conventional predictions?
– Are new physics really necessary?
– Freak waves – rare realizations of a typical extreme wave population or typical realizations of a rare extreme wave population?
– Are extreme waves the largest ever recorded?
– Were freak waves involved in the sinking of [this or that ship]?
– Are rogue waves a problem for structural design?
– Are there particular oceanographic conditions in which freak waves are more probable?
– Do extreme waves appear in groups (the "Three (nine) Sisters" of mariners' lore)?
– Can a "wall of water" be spotted enough in advance to allow time for safety measures?
– Can one identify and track a group within which a rogue wave might suddenly appear?
– Modeling a "rogue wave" – speculations or realistic possibility?
– What factors limit extreme wave heights?
– Can the Benjamin-Feir instability spawn a rogue wave?
– Rogue waves and wave breaking – how are these phenomena related?
– What effect does the wind produce on the kinematics and dynamics of rogue waves?

The purpose of this book is to show the progress that is being made in approaching the answers in the list above as well as other questions, and to consider some new questions that should be answered in the future. The main attention will be focused on the physical mechanisms of rogue wave generation brought into correlation with experiments and natural observations.

List of Notations

AI	abnormality index
C_{ph}	phase velocity
g	acceleration due to gravity
H	wave height
H_{cr}	wave crest height
H_{fr}	height of the freak wave
H_s	significant wave height
K	wavenumber
S	wave steepness
T	wave period
U_w	wind velocity
X	coordinate along the wave propagation
λ	Wavelength

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