Lecture 4

Irregular waves

4.1 The statistical representation of irregular waves

The confused state of the sea at any point can be modeled in 3D as the interference pattern created between several wave systems. These random wave systems are often at different phases in their development and at differing distances from the observation point. Sea modelling is made possible by applying the principle of superposition according to which the complicated sea wave system is made up of many sinusoidal wave components superimposed upon each other. Each component sine wave has its own wavelength, speed and amplitude and is created from one of the wave energy sources (see Figure 4-1).

(a) 3D model (b) 2D model

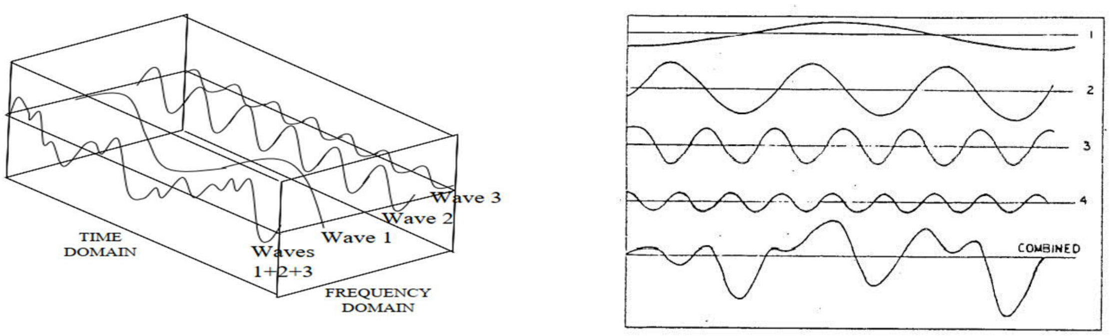


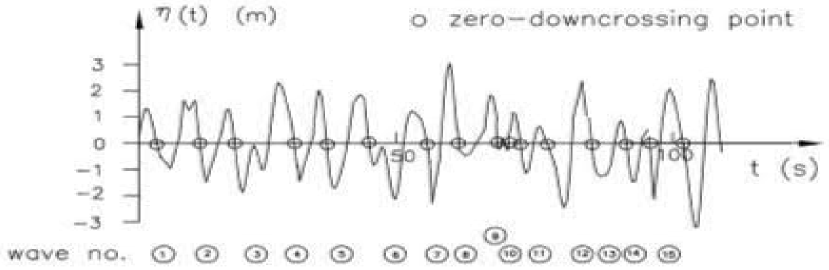
Figure 4-1 The superposition of irregular waves

Irregular waves can be understood within the context of Gaussian statistics. The amplitude and frequency of the component waves are selected from the wave spectra (mean square spectral density functions) which are a measure of the wave energy. The response to the irregular seaway is therefore a superposition of the responses of each regular wave. This analysis is analogous to the representation of non-sinusoidal periodic excitations and responses using Fourier analysis (see section 4.2).

The main assumptions maintained in the statistical approach is that the sea is stationary, its statistical properties (e.g. average wave and period) do not change within a considered time frame and the seaway is not too steep so that the linear superposition of a regular number of waves and the utilization of the linearized equations are still accurate.

For a regular wave, the wavelength is the distance between two successive crests or troughs. For irregular waves, the individual wave is defined by *two successive zero down-crossings.* In a real wave recording there will be hundreds of individual waves. The simple example shown in Figure 4-2 comprises of 15 individual waves ordered in time by height, zero crossing periods and wave number.

A histogram can be used to evaluate the range of water elevation variation (e.g. see Figure 4-3). To create such histogram water surface measurements at a particular location are made at regular intervals (say, every 1 minute). The measurements at a particular location are then grouped into elevation ranges.



rank i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
H (m)	5.5	4.8	4.2	3.9	3.8	3.4	2.9	2.8	2.7	2.3	2.2	1.9	1.8	1.1	0.23
T (s)	12.5	13.0	12.0	11.2	15.2	8.5	11.9	11.0	9.3	10.1	7.2	5.6	6.3	4.0	0.9
wave no. in 5.2	7	12	15	3	5	4	2	11	6	1	10	8	13	14	9

Figure 4-2 Irregular wave record table measured by a buoy

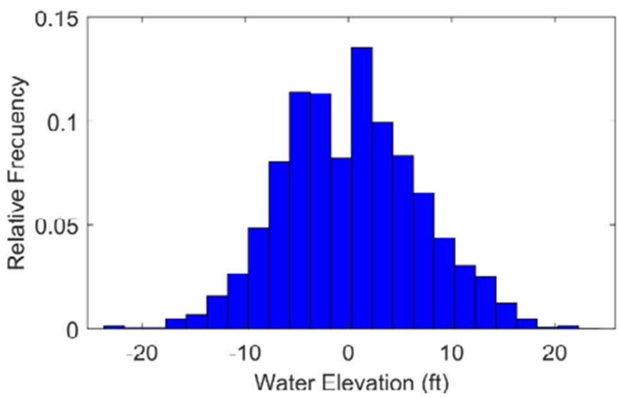


Figure 4-3 Example of water elevation histogram

The easiest statistical measures to work with are means and averages; e.g. average all the measurements of the water elevation (ζ) to obtain the mean water level $\bar{\zeta}$. We can also measure the mean peak amplitude for every wave in the signal $\bar{\zeta}_a$. Then the mean wave height is defined as twice the mean wave amplitude:

$$H_a = 2 \times \bar{\zeta}_a \tag{4-1}$$

The time between each peak can also be measured T_p and then averaged to give the mean period of the peaks $\overline{T_p}$. The time between zero crossings (i.e. the time between the water surface passing up through the nominal zero water level) can be measured for all waves as T_z and averaged as $\bar{T_z}$. Then the mean of any *N* set of numbers (*x*) is given by:

$$\bar{x} = \sum_{n=1}^{N} \frac{x_n}{N} \tag{4-2}$$

So the mean water elevation is:

$$\bar{\zeta} = \sum_{n=1}^{N} \frac{\zeta_n}{N} \tag{4-3}$$

where *N* is the no. of measurements and ζ_n is each measurement of the water surface. The variance of a set of numbers is a measure of how spread out the data are (i.,e. how far the numbers lie from the mean). The variance of the water elevation then is written as:

$$m_0 = \sum_{i=1}^{N} \frac{(\zeta_n - \bar{\zeta})^2}{N} \tag{4-4}$$

The standard deviation is another measure of the dispersion of the data. if the standard deviation is small the data points are close to the mean. If the standard deviation large the data points are spread out over a large range of values. The standard deviation is equal to the square route of the variance ; i.e.

$$\sigma_0 = \sqrt{m_0} \tag{4-5}$$

For meaningful results the data must include at least 100 pairs of peaks and troughs.

In ship dynamics and naval architecture a useful concept used to explain waves is the significant wave heights and periods defined as the average wave height and period of one-third of the highest waves. This is because the design of ship structures has been traditionally based on experiences and visual observations of the waves which concentrate only on the significant wave heights. For example, based on the tabulated values of Figure 4-2 the 1/3 of the total number of individual waves is 5, and the 5 most significant wave heights are chosen as:

$$H_S = H_{1/3} = \frac{1}{5}\sum_{i=1}^{5} H_i = \frac{1}{5}(5.5 + 4.8 + 4.2 + 3.9 + 3.8) = 4.44\ m \tag{4-6}$$

Accordingly, the significant period becomes:

$$T_s = T_{1/3} = \frac{1}{5}\sum_{j=1}^{5} T_i = 12.9\ s \tag{4-7}$$

On occasion the significant wave height is taken as the average of only (1/10) of the total number of ensembles ($H_{1/10}$). The maximum wave height $H_{\max}$ among a long-time record e.g. 100 years is often used when designing an offshore structure. In naval architecture practice, the wave height might be denoted by its probability of exceedance. Thus, wave data histograms are usually represented in a non-dimensional form to allow for comparison of waves in different locations. The wave height is divided by the average wave height and plotted against the probability density. The Rayleigh probability density function used in such representations (see Figure 4-4) is defined as:

$$f(H/\bar{H}) = \frac{\pi}{2}(H/\bar{H}) \cdot e^{-\pi/4(H/\bar{H})^2} \tag{4-8}$$

A benefit we can gain from the use of such approach is that we can represent the characteristic wave heights as a function of the average wave height of the histogram. A reservation on the utilization of Rayleigh distribution is that it loses validity when applied to broad spectrum (i.e. wave idealization of wave high energy spreads over wide range of frequencies).

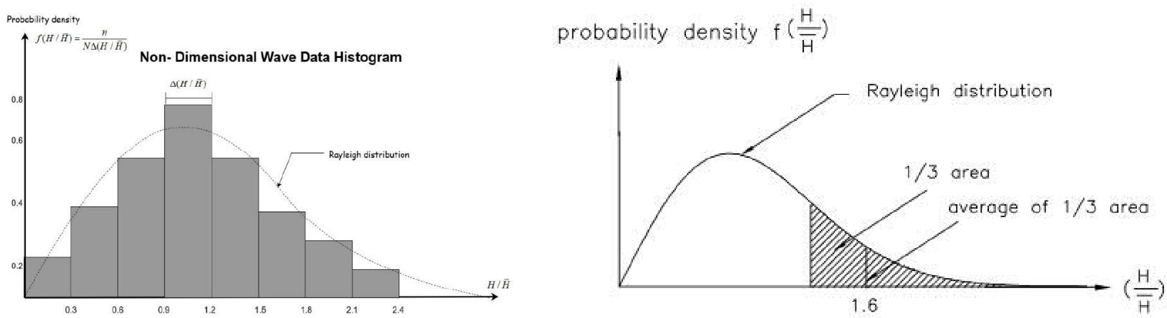


Figure 4-4 Wave data histogram (b) non-dimensional wave data histogram and Rayleigh distribution

4.2 Wave superposition and Fourier analysis

Let us consider two waves travelling past the same point (say *x = 0*) that have the same amplitude, ζ_0 but different frequencies ω_1, ω_2. Their corresponding wave elevations will be presented as:

$$\zeta_1(t) = \zeta_0 \sin(\omega_1 t) \tag{4-9}$$

$$\zeta_2(t) = \zeta_0 \sin(\omega_2 t) \tag{4-10}$$

The water elevation at this point will be the sumo f the two waves travelling past, i.e. $\zeta(t) = \zeta_1(t) + \zeta_2(t)$. Figure 4-5 shows how two waves of the same wave amplitude but different frequencies combine to form a new wave. If we change the wave amplitude and add a phase angle the combined wave changes. The more waves of different frequencies, amplitudes and phase angles are used the more complex the resulting water elevation becomes. For example, Figure 4-6 shows a wave train comprising of 50 frequency components. In the same way we can create an irregular wave train by combining many frequency components of different frequencies we can identify the different frequency components in a given wave train using a Fourier Transform (FT). An FT helps to identify the amplitude and phase angle of each frequency component in the wave. We can consider the wave time history to represented by the sum of all of these components added to the mean water elevation as :

$$\zeta(t) = \bar{\zeta} + \sum_{n=1}^{N} \zeta_{n0} sin(\omega_n t + \varepsilon_n) \quad (4\text{-}11)$$

where ω_n represents each signal wave frequency and $\zeta_{n0}\ and\ \varepsilon_n$ are the corresponding wave amplitude and phase angle.

If a wave signal consists of a single sinusoid finding the frequency content will result in a single number. However, in reality all signals contain some noise. The discrete FT (DFT) helps to convert a sequence of values corresponding to certain time instants to a sequence of values corresponding to specific frequencies.

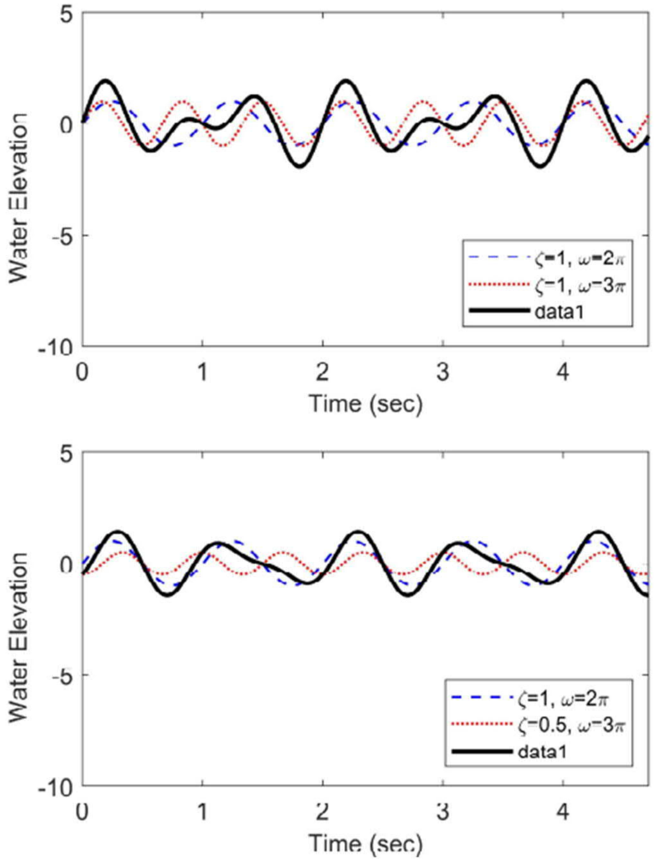


Figure 4-5 Superposition of two waves

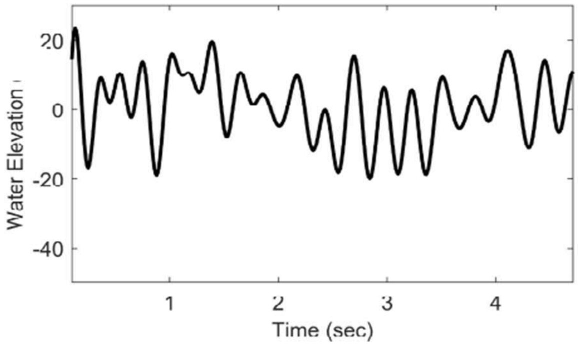


Figure 4-6 *Superposition of 50 wave components*

The most common DFT is the so-called Fast Fourier Transform (FFT). The time domain consists of a set of numbers (x_0, x_1 , ..., x_n) each measured at a particular time (t_0, t_1,...,t_n). The DFT provides the frequency domain information of numbers (X_0, X_1, ...,X_n) where each X_k represents a portion of the signal that occurs at a frequency component, say f_k. By convention *n* refers to the time domain data point and *k* refers to the frequency domain data point. The frequency values of X_k are typically complex numbers (expressed in real and imaginary parts). If we have *N* data points in time (x_n) we will have only *N/2* points in the frequency domain. This is because for each frequency we have two pieces for information; namely the magnitude and the phase – while at each time we only have one piece of information namely ''*magnitude*''. In the time domain data have an associated sampling frequency (samples / second). This relates to the time interval between data points (*Dt*) as follows :

$$f_s = \frac{1}{Dt} \tag{4-12}$$

For example if we take 100 regularly spaced measurements in 0.5 second we have a sample of 100 data points (*N* = 100). The time between samples is found by dividing the total time by the total number of samples. So if we take a sample every 0.005 seconds (i.e. 0.5 secs divided by 100 samples) then :

$$Df = \frac{f_s}{N} \tag{4-13}$$

where *Df* is the frequency resolution. So in this example we have frequency resolution of 2Hz (= 200 Hz / 100 samples). The raw form of the frequency information that FFT delivers is not in a physically meaningful form (e.g. values are complex). Thus, we need to scale the results to find amplitudes and phase. To find the amplitude we need to take the absolute magnitude of the complex number, multiply it by 2 and divide by the total number of points :

$$Magnitude = 2\frac{|X_k|}{N} \tag{4-14}$$

where X_k is the complex number at frequency **k**. The phase angle information is determined form taking the tangent of the real and complex parts of the FFT output. The process of FFT is mathematically complex but MATLAB can be used to obtain X_k. Following this scaling iof the magnitude and phase should be done manually. The fastest oscillation (i.e. the highest frequency) depends on how rtapidly the data is sampled. Therefore it can be measured as:

$$f_{max} = \frac{N}{2} Df \tag{4-15}$$

which is known as the Nyquist frequency.

4.3 Wave energy spectrum

In an random sea the total energy is a sum of the energies of each of the regular waves comprising the irregular sea and is defined as :

$$E_{TOT} = \frac{1}{2}\rho g(\zeta_{a1}^2 + \zeta_{a2}^2 + \cdots + \zeta_{an}^2) \tag{4-16}$$

The importance of wave components (each sinusoidal wave) making up the time history of an irregular wave pattern may be quantified in terms of a wave amplitude energy spectrum known as the wave energy spectrum (see Figure 4-7). The time history of the water elevation is :

$$\zeta_t = \bar{\zeta} + \sum_{n=1}^{\infty} \zeta_{i0} \sin(\omega_i t + \varepsilon) \tag{4-17}$$

The area under the curve depicted in Figure 4-7 equals the energy of that frequency component. The spectral ordinate $S_\zeta(\omega_n)$ is the value on the vertical axis of Figure 4-7. Thus the spectral ordinate for each frequency is :

$$S_\zeta(\omega_i) = \frac{\zeta_{i0}^2}{2\delta\omega} \tag{4-18}$$

If the energy spectrum is known it is possible to reverse the spectral analysis process and generate a corresponding time history by adding a large number of component sine waves as per Eq.(4-17). The measured time history of the water surface elevation and the wave energy spectrum are both representations of the same information – the seaway. The variance is a measure of the degree of spread in the wave surface and wave amplitudes are a measure of the wave energy. For water elevation the larger the waves the larger the variance and higher the energy in the seaway. The equation of the variance is $m_0 = \sum_{i=1}^{N} \frac{(\zeta_n - \bar{\zeta})^2}{N}$ (see lecture 3). *An alternative definition is the variance of the irregular time history is equal to the area under the energy wave spectrum.* Thus,

$$m_0 = \int_0^\infty S_\zeta(\omega) d\omega \tag{4-19}$$

The wave energy spectrum $S_\zeta(\omega)$ is determined from the wave amplitudesa and frequencies from a DFT of the wave time history. Therefore the wave velocity spectrum $S_{\dot{\zeta}}(\omega)$ and the wave acceleratin spectrum $S_{\ddot{\zeta}}(\omega)$ are defined by using the velocity and acceleration amplitudes and frequencies as :

$$S_{\dot{\zeta}}(\omega) = \omega_i^2 S_\zeta(\omega_i) \tag{4-20}$$

$$S_{\ddot{\zeta}}(\omega) = \omega_i^4 S_\zeta(\omega_i) \tag{4-21}$$

In general the relationship between a spectral moment and the wave energy curve is :

$$m_n = \int_0^\infty \omega^n S_\zeta(\omega) d\omega \tag{4-22}$$

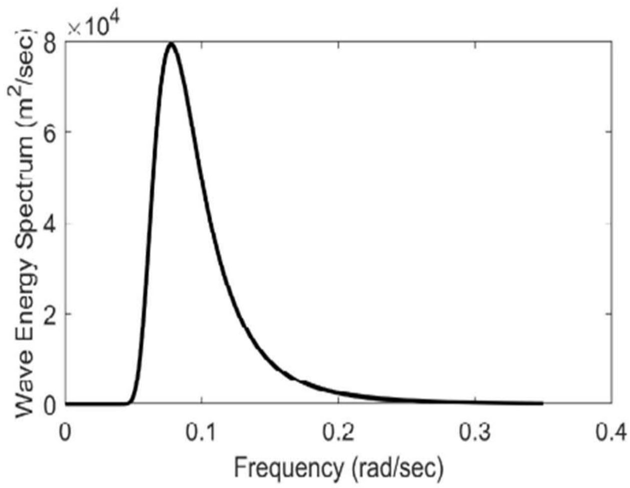
Thus, the second and fourth order spectral moments are defined as

$$m_2 = \int_0^\infty \omega_i^2 S_\zeta(\omega_i) \tag{4-23}$$

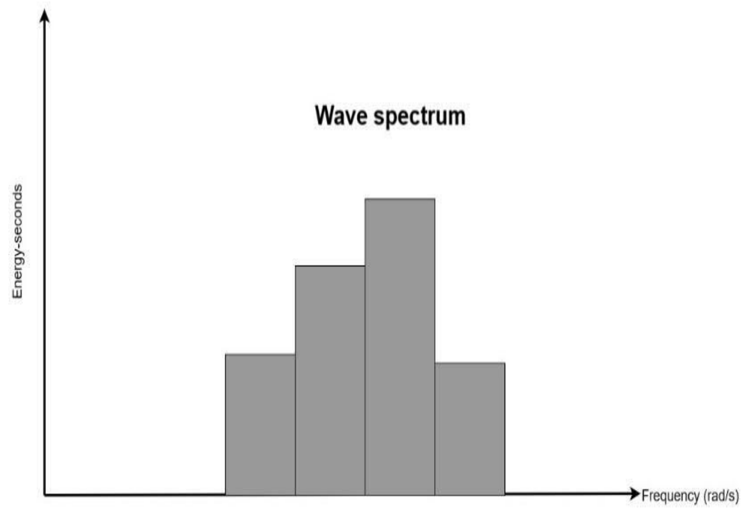
$$m_4 = \int_0^\infty \omega_i^4 S_\zeta(\omega_i) \tag{4-24}$$

These spectral moments can be used to link the spectra to the statistical characteristics of Table 4-1:

(a) General model



(b)Example of four wave spectrum



(b) Example of irregular wave spectrum

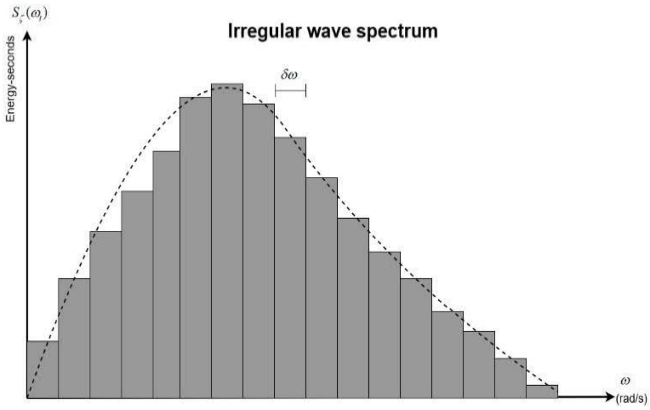


Figure 4-7 Wave energy spectrum

Table 4-1 Wave characteristics associated with spectral moments

Mean Frequency	$\bar{\omega} = \frac{m_1}{m_0}$
Mean period	$\bar{T} = \frac{2\pi}{\bar{\omega}} = 2\pi\frac{m_1}{m_0}$
Mean peak period	$\bar{T}_P = 2\pi\sqrt{\frac{m_2}{m_4}}$
Mean zero-crossing period	$\bar{T}_z = 2\pi\sqrt{\frac{m_0}{m_2}}$

The spectrum bandwidth describes the relative width of the wave energy spectrum compared to the height. A narrow band spectrum is concentrated in a narrow range of frequencies and little or no energy in other frequencies. In a wide band spectrum the energy is distributed among wide range of frequencies. A parameter that may be used to measure the band narrowness of a wave spectrum using the spectrum moments is the *bandwidth parameter* defined as the ratio between average period of the peaks and the average zero-crossing period according to the equation :

$$\varepsilon = \sqrt{1 - \frac{\bar{T}_P^2}{\bar{T}_z^2}} = \sqrt{1 - \frac{m_2^2}{m_0 m_4}} \qquad (4\text{-}25)$$

As the bandwidth parameter approaches zero, the spectrum becomes extremely narrow. On the other hand, as the bandwidth parameter approaches one it becomes extremely broad.

4.4 Idealized wave spectra

When observing the ocean's surface, one sees a procession of seemingly random waves. The variation in surface elevation over time makes up what is referred to as a time series. For practical analysis it is usual practice to convert this time series to a frequency domain, or spectral, representation of the same data. The wave spectrum is much more useful for assessing the vessel's performance than the time series data. Naval architects have developed mathematical expressions known as idealized wave spectra. These describe the distribution of wave energy with frequency for a specified wave height and period.

Sea waves are primarily the result of wind transferring energy to the sea surface. The kinetic energy of the wind (wind speed) creates potential energy of the water (waves). The height and length of the generated waves depends on the wind velocity, the length of time wind blows over the water surface and the fetch ; i.e. the distance of water over which the wind blows before reaching the land. Open oceans have infinite fetch. bays, lakes and coastal area are limited fetch area and comprise of waves that are shorter (higher frequency) and steeper. If there are no fetch limitations waves reach an equilibrium where the amount of energy transferred from the wind maintains the wave heights. However the dissipation of the water (viscous and wave breaking) prevents additional amplitude growth. A sea at this condition is known as fully developed. For ship design purposes we use different formulae to represent open ocean and coastal (limited fetch) wave conditions. The first ocean spectra model considered is Pierson Moskowitz (1964) one parameter wave spectrum. The only input of this wave spectrum is wind speed. The spectrum assumes there is plenty of area for the wind/water interface and the wind has been blowing for long enough so that the wave field has reached a state of equilibrium. The derivation of this spectrum has been based on extensive measurements in the North Atlantic Ocean and it is intended to represent the spectrum of fully developed seas as follows:

$$S_\zeta(\omega) = \frac{0.0081g^2}{\omega^5} e^{-0.74\left(\frac{g}{W_{19.5\omega}}\right)^4} \tag{4-26}$$

where $W_{19.5}$ is the average wind speed in m/s at 19.5 m above the sea surface. The units for the spectrum are m^2/sec. Since 19.5 meters is not a typical height for wind measurements this can be related to the more standard 10 meters by $W_{19.5} = 1.026\ W_{10}$ (see Figure 4-8).

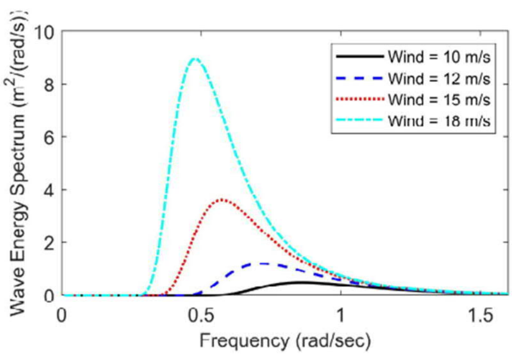


Figure 4-8 Example Pierson Moskowitz spectra for different wind speeds

Another open ocean wave spectrum is the ITTC (International Towing Tank Conference) 1973 Bretschneider's spectrum. This is a two parameter spectrum that depends on the given significant wave height and modal period (i.e. the period that coincides with the peak of the wave energy spectrum) as follows:

$$S_\zeta(\omega) = \frac{1.25}{4}\left(\frac{\omega_0}{\omega}\right)^4 \frac{\overline{H}_{\frac{1}{3}}^2}{\omega} e^{-1.25\left(\frac{\omega_0}{\omega}\right)^4} \quad (4\text{-}27)$$

where $H_{1/3}$ is the significant wave height, ω_0 is the modal wave frequency ω_0=($\omega_0 = \frac{2\pi}{T_0}$, where T_0 is the modal wave period). Figure 4-9 shows various ITTC wave spectra for different wind speeds.

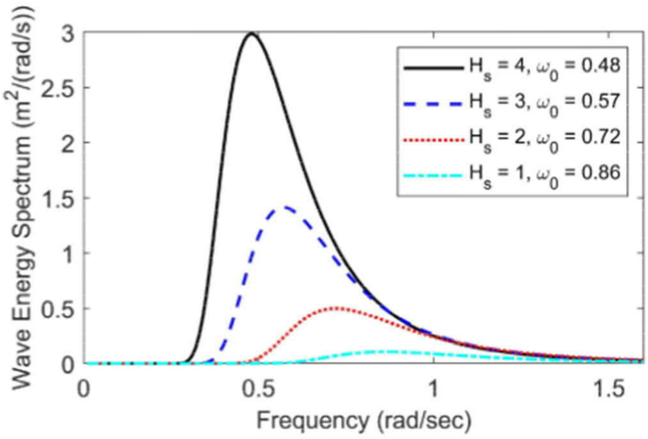


Figure 4-9 Example of ITTC (Bretschneider) spectra for different significant wave height / modal period combinations.

For limited fetch conditions we typically use the Jonswap (Joint North Sea Wave Observation Project) spectrum. This is intended to represent open wave conditions but where the fetch is limited (i.e. like the North Atlantic). The spectrum is more narrow; i.e. has higher peaks than the pure open ocean spectra. It is a three parameter spectrum that considers speeds, fetch and steepness factor (γ) as follows :

$$S_\zeta(\omega) = \frac{ag}{\omega^5} e^{-\left(\frac{5\omega_0^4}{4\omega^4}\right)} \gamma^r \quad (4\text{-}28)$$

where a depends on whether the spectral ordinate being calculated is less than or greater than the wave modal frequency defined as

$$\sigma = \begin{cases} 0.07 \; if & \omega \le \omega_0 \\ 0.09 \; if & \omega > \omega_0 \end{cases} \quad (4\text{-}29)$$

The parameter γ is the "steepness factor" and can be modified to meet the needs of the sea conditions. It ranges from about 1 to about 7, but a typical value for 7 is 3.3. The Jonswap spectrum can also be expressed as a function of significant wave height, modal frequency and γ as:

$$S_\zeta(\omega) = B_j \overline{H}_{1/3}^2 \frac{2\pi}{\omega}\left(\frac{\omega_0}{\omega}\right)^4 e^{-\left[\frac{5}{4}\left(\frac{\omega_0}{\omega}\right)^4\right]} \gamma^r \quad (4\text{-}30)$$

where: $B_j = \frac{0.06238}{0.230+0.0336\gamma-\frac{0.0185}{1.9+\gamma}}[1.094 - 0.01915 ln\gamma]$ and r and γ are the same as defined above. This formulation makes it easier to see how the limited fetch changes the wave energy distribution compared with fully open ocean ITTC spectrum. Figure 4-10 shows several generated Jonswap spectra for the same significant wave heights and modal wave periods as used in the ITTC spectra with steepness factor 2.

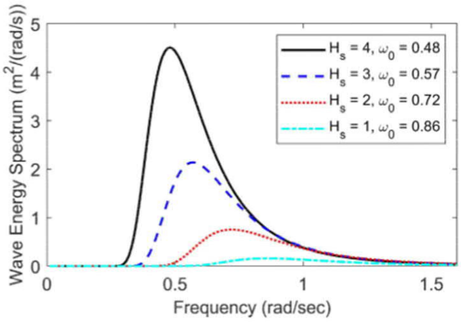


Figure 4-10 Example of Jonswap spectra for different wind speed and fetch combinations.

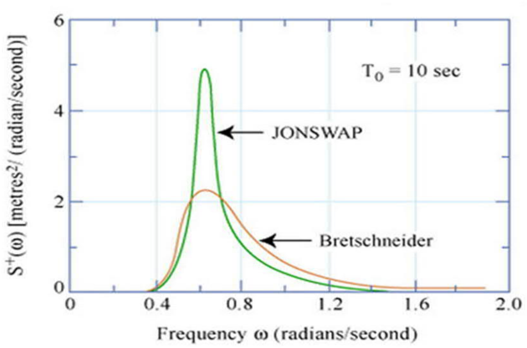


Figure 4-11 *Comparison of steepness difference between Jonswap &* Bretschneider spectra for $H_{1/3}$= 4m

4.5 The statistics of sea states

We have discussed in the first sections of this lecture how the spectrum can be idealized using some wave characteristics corresponding to wave records or measurements such as the significant wave height and period. In open seas these characteristics vary depending on the area of operation. Naval architects need to choose specific values of the wave characteristics in different locations and seasons. A summary of these data is included in the atlas of *Global Wave Statistics* developed by British Maritime Technology. The data are divided into different numbered regions Figure 4-12. They are subdivided into different wave directions and presented in the form of scatter diagrams, giving the joint probability of occurrence in parts per thousand for combinations of significant wave height and zero crossing period occurring simultaneously (see Figure 4-13). For instance, the probability of occurrence of wave heights from all directions in the range of 6-7 meters with periods range of 9-10 seconds is 32/1000=0.032. The right hand of each diagram is the probability of occurrence of each significant wave height range for all wave periods, while on the probability of occurrence of each significant wave period range for all wave periods is shown in the top or the bottom of each diagram. North Atlantic (Area 9) especially in the winter season and the North Sea (Area 11) are the most critical areas. Global wave statistics may deviate from modern satellite measurements because (1) they were formed in the 1960s and since then due to global warming the environmental conditions changed; (2) they are based on visual observations and since masters usually avoid heavy weather conditions while sailing, which gives some fair weather-biased statistics and underestimation of significant wave heights and periods.

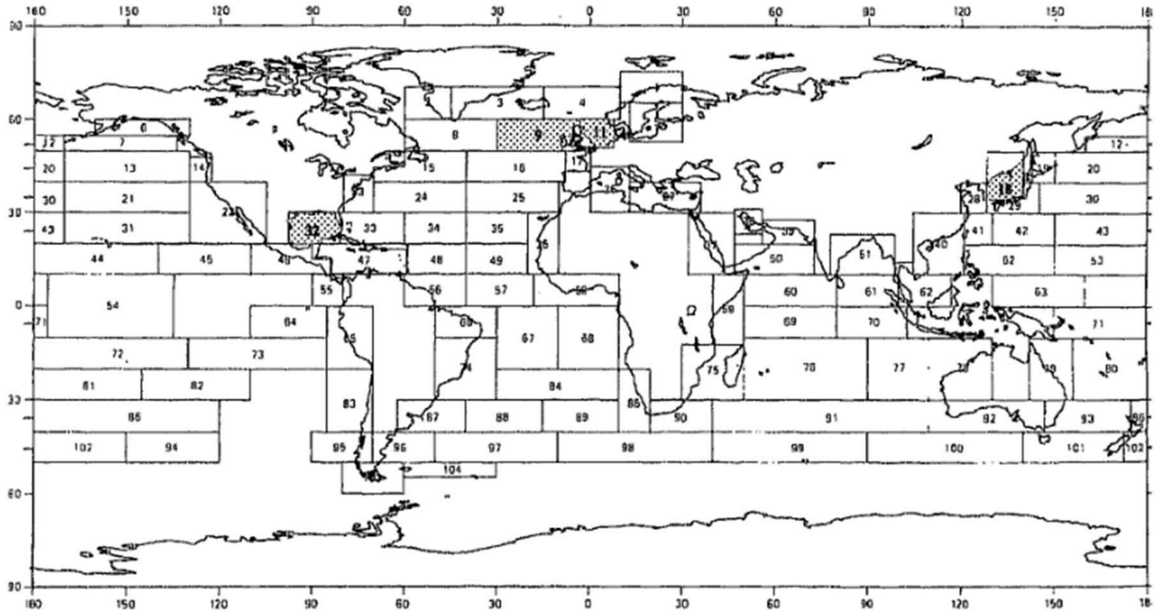


Figure 4-12 Wave Atlas (Hogben, Dacunha, and Olliver 1986)

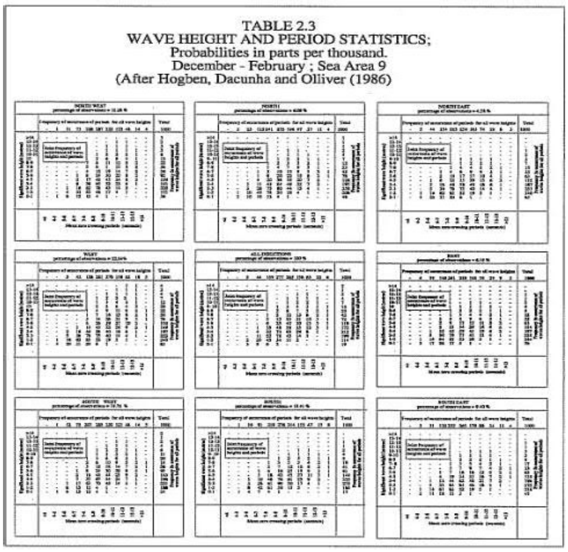


TABLE 2.3
WAVE HEIGHT AND PERIOD STATISTICS;
Probabilities in parts per thousand.
December - February ; Sea Area 9
(After Hogben, Dacunha and Olliver (1986)

Area 9; December to February; North West; Percentage of observations = 11.28%

Significant wave height [m] \ Zero Crossing Period [s]	< 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	> 13	Total
Total	0	1	10	73	210	286	236	120	50	14	0	1000
> 14												0
13 - 14								1	1			2
12 - 13							1	1	1			3
11 - 12							1	2	1	1		5
10 - 11						1	2	2	2	1		8
9 - 10						2	4	4	2	1		13
8 - 9					1	3	6	7	4	1		22
7 - 8					2	6	11	10	5	2		36
6 - 7					4	12	19	14	8	2		59
5 - 6				1	8	24	31	22	8	2		96
4 - 5				2	17	43	44	25	8	2		141
3 - 4				6	37	66	53	14	6	1		183
2 - 3			1	16	63	76	46	14	3	1		220
1 -2			4	33	66	49	17	4	1			174
0 - 1		1	5	15	12	4	1					38

Figure 4-13 Different area wave statistics (Hogben, Dacunha, and Olliver 1986)

Sea State Number	Significant Wave Height (ft)		Sustained Wind Speed (Kts)		Percentage Probability of Sea State	Modal Wave Period (s)	
	Range	Mean	Range	Mean		Range	Most Probable
0-1	0-0.3	0.2	0-6	3	0	-	-
2	0.3-1.5	1.0	7-10	8.5	7.2	3.3-12.8	7.5
3	1.5-4	2.9	11-16	13.5	22.4	5.0-14.8	7.5
4	4-8	6.2	17-21	19	28.7	6.1-15.2	8.8
5	8-13	10.7	22-27	24.5	15.5	8.3-15.5	9.7
6	13-20	16.4	28-47	37.5	18.7	9.8-16.2	12.4
7	20-30	24.6	48-55	51.5	6.1	11.8-18.5	15.0
8	30-45	37.7	56-63	59.5	1.2	14.2-18.6	16.4
>8	>45	>45	>63	>63	<0.05	15.7-23.7	20.0

Figure 4-14 NATO (STANAG 4194) Sea State Numeral Table for the Open Ocean North Atlantic

4.6 Extreme waves

Freak waves (or rogue or abnormal waves) are an open water phenomenon, in which winds, currents, non-linear phenomena such as solitons, and other undefined circumstances cause a wave to briefly form a far larger wave. They are considered rare but potentially very dangerous, since they can involve the spontaneous formation of massive waves far beyond the usual expectations of ship designers, and can overwhelm the usual capabilities of oceangoing vessels which are not designed for such encounters. The underlying physics that makes phenomena such as rogue waves possible is that different waves can travel at different speeds, and so they can "pile up" in certain circumstances, known as ''*constructive interference*''. In deep ocean the speed of a gravity wave is proportional to the square root of its wavelength, i.e., the distance peak-to-peak between adjacent waves. Other situations can also give rise to rogue waves, particularly situations where non-linear effects or instability effects can cause energy to move between waves and be concentrated in one or very few extremely large waves before returning to ''*normal*'' conditions. Eyewitness accounts from mariners and damage inflicted on ships have long suggested that they occur more frequently than originally thought. The first scientific evidence of their existence came with the recording of a rogue wave by the Gorm platform in the central North Sea in 1984. A stand-out wave was detected with a wave height of 11 metres in a relatively low sea state. However, what caught the attention of the scientific community was the digital measurement of a rogue wave at the Draupner platform in the North Sea on January 1, 1995. This is known as the ''*Draupner wave*''. It had a recorded maximum wave height of 25.6 metres. During that event, minor damage was inflicted on the platform far above sea level. Since then the existence of freak waves has been confirmed by video and photographs, satellite imagery, radar of the ocean surface, stereo wave imaging systems, pressure transducers on the sea-floor, and oceanographic research vessels.In February 2000, the British oceanographic research vessel, RRS Discovery, was sailing in the Rockall Trough west of Scotland. She encountered the largest waves ever recorded by any scientific instruments in the open ocean, with a significant wave height of 18.5 meters and individual waves up to 29.1 metres. In 2004 scientists using three weeks of radar images from European Space Agency satellites found ten rogue waves, each 25 meters or higher. A rogue wave is a natural ocean phenomenon that is not caused by land movement, only lasts briefly, occurs in a limited location, and most often happens far out at sea.

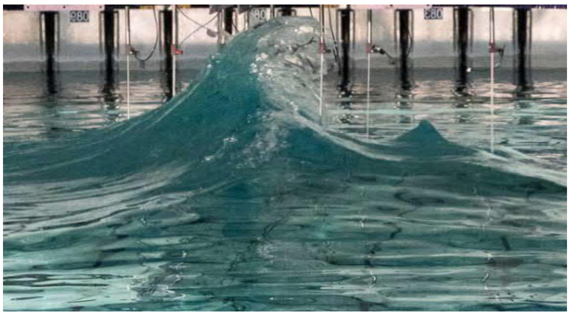


Figure 4-15 Reconstruction of the Draupner wave (McAllister et al. 2019).

Rogue waves are, therefore distinct from "*tsunamis*" that are caused by a massive displacement of water, often resulting from sudden movements of the ocean floor, after which they propagate at high speed over a wide area. They are nearly unnoticeable in deep water and only become dangerous as they approach the shoreline and the ocean floor becomes shallower. Tsunamis do not present a threat to shipping at sea. They are also distinct from (a) mega tsunamis, which are single massive waves caused by sudden impact, such as meteor impact or landslides within enclosed or limited bodies of water and (b) the "*hundred-year wave*" which is a purely statistical prediction of the highest wave likely to occur in a hundred-year period in a particular body of water.

Figure 4-16 *Waves approach Miyako City after a 9.0 magnitude earthquake hit Japan. This tsunami led to more than 15,000 deaths (Image credit: NBC News 4.12.2018)*

4.7 References

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STANAG 4194. NATO Standardized Wave and Wind Environments and Shipboard Reporting of Sea Conditions.