CHAPTER 10

EXTREME WAVE PARAMETERS BASED ON CONTINENTAL SHELF STORM WAVE RECORDS

by

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SUMMARY

Measured storm wave records from several Continental Shelf areas were used to test the adequacy of estimating formulae for individual wave parameters. In all, 376 hours of storm wave records were analyzed, and their properties nondimensionalized by fundamental spectral parameters. Results are presented for surface deviation statistics, individual wave height statistics and individual wave period statistics. The results can be used by ocean engineers to eliminate unintended bias from wave parameters selected for the design of offshore facilities. The most significant result is that measured rare wave heights in the storm wave records are on the order of 10 percent less than predicted by the Rayleigh distribution at the 1 in 1000 probability level.

INTRODUCTION

Severe storms on the Continental Shelf produce a complex series of waves in time and space. The condition of the ocean's surface which exists over a short time interval is assumed to be a stationary process called a sea state. The spectral definition, a distribution of the amplitude energy density in the frequency domain, contains the necessary information to define the sea state. Fundamental properties derived from the spectral definition are the total energy content (or variance of the sea surface) and the dominant frequency (or frequency of maximum energy density). The shape of the spectral density function is also important because it characterizes the wave amplitude record. Modern wave prediction methods estimate the energy content of the sea surface as a function of both frequency and direction [1]. Instrumental measurements of the stationary, time-varying sea surface can be analyzed mathematically to produce the spectral density as a function of frequency. Such instrumental measurements are often used to verify or calibrate numerical wave prediction models. Figure 1 illustrates the typical sea state spectrum and the derived properties which will be used in this paper.

Conventional engineering design practice for fixed offshore structures requires the specification of an individual wave in terms of trough-to-crest height and zero-crossing period [2]. This design wave should be a realistic estimate of the extreme, rare wave in a severe storm sea state whose return period is appropriate for the design

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problem at hand and whose properties are consistent with real sea surface behavior. Selection of design wave parameters is often based on the assumption that the distribution of wave heights in a storm sea state is described by the theoretical Rayleigh distribution. Practical formulae for the selection of wave parameters have been proposed based on this assumption. These formulae can be expressed in terms of the fundamental derived properties from the amplitude energy density spectrum. However, an idealized sea surface is assumed; that is, the distribution of surface deviations about the mean is Gaussian and the energy is narrow-banded in the frequency domain. Neither of these assumptions is satisfied for storm wave records on the Continental Shelf. Jahns and Wheeler [4] have shown that substantial deviations from the Gaussian assumption occur in water depths up to 100 ft. Furthermore, reported storm wave spectra and spectral hindcasts made by modern wave prediction methods may not be sufficiently narrow-banded to justify that assumption. A study was undertaken using measured storm wave records from several Continental Shelf areas to test the adequacy of estimating formulae for individual wave parameters. The results reported in this paper will allow the designer to avoid any unintended bias in selecting design wave parameters. The results also provide a basis for the development of empirical compensation factors for practical use.

DATA SOURCES AND ANALYSES

The offshore petroleum industry has undertaken several measurement programs in areas of present and future interest. Valuable wave records have been obtained in the Gulf of Mexico through the Ocean Data Gathering Program [5], in the North Sea through a measurement program sponsored by the United Kingdom Offshore Operators Association and through the Gulf of Alaska Wave and Wind Measurement Program [6]. Exxon has also obtained storm wave data in conjunction with offshore operations. Analysis of these data is restricted to digitized storm wave records. The arisen sea states provide the opportunity to examine greater deviations from the idealized sea surface than would be expected under ambient wave conditions. Compensation factors developed from the measured storm data should be applicable to design problems because the underlying physical phenomena are similar to those that occur under design level conditions.

Table 1 summarizes the data sources utilized in this study. Widely different geographic areas, water depths, and measurement systems are combined in the results presented in this paper. Altogether, approximately 376 hours of storm wave records were analyzed.

TABLE 1 Summary of Data Sources Utilized

	Gulf of Mexico	Offshore Australia	Northern North Sea	Gulf of Alaska
Locations	Various	38°59'S, 142°33'E	60°20'N, 0°E	Various
Dates	Various	May, 1968	Nov, 1973-Jan, 1974	Nov, 1974-Feb, 1975
No. of Stormy Intervals	7	1	8	6
Water Depth	34-340 ft	327 ft	522 ft	366-600 ft
Minimum H_s	8 ft	15 ft	15 ft	15 ft
Measurement System	Wavestaff (fixed platform)	Heave-Compensated Wavestaff (semi-submersible)	Waverider Buoy	Waverider Buoy

Many investigators have presented characteristic spectra based on wave measurements. The principal ones applied to continental shelf storms are due to Pierson and Moskowitz [7], Robinson, Brannon and Kattawar [8] and Hasselmann et al [9, 10, 11]. These spectra are compared in a nondimensionalized form in Fig. 2. The dimensionless groups used here place the dominant spectral frequency at unity and require that the area under the spectrum be unity. Thus, the spectral density shapes in the frequency domain can be compared directly. The storm wave data analyzed in this study exhibit a broad range of spectral shapes which include all three of the model shapes illustrated in Fig. 2. This is not unexpected because of the variety of meteorological conditions represented by the data. The storm waves in the Gulf of Mexico are produced by tropical storms with their attendant high winds and rapidly changing wind fields. North Sea and Gulf of Alaska storms are produced by large extratropical disturbances which have lower wind speeds but greater fetch lengths and durations. In some cases there is swell propagating into the wind fetch area which alters the character of the storm spectra.

Statistical analyses of the storm wave records were conducted in a hierarchy outlined below:

Data Blocks - Continuous water surface deviation records were digitized, and approximately 20-minute segments were analyzed as a block. A 20-minute wave record is considered long enough to obtain statistically meaningful results, but short enough to warrant the assumption of a stationary, ergodic process. The data were screened to insure that no noise spikes, DC drifts or original analog signal lapses would be inadvertently incorporated into the statistical analysis. An amplitude energy density spectrum was computed for each block of storm wave data. This defined the dominant spectral frequency and the spectral moments for the block. The spectral calculations were conducted by the methods of Blackman and Tukey

[12] with the number of lag products used for the autocorrelation function calculation equal to approximately 100/Δt. Statistics on individual wave crest elevations, heights and zero-crossing periods were accumulated from the wave record. Other special parameters which will be discussed later were also computed for each block of data. Quantities derived from the wave record analysis were nondimensionalized by fundamental spectral parameters. Wave crest and height parameters were nondimensionalized by $\sigma = \sqrt{m_o}$ and wave period parameters were nondimensionalized by T_d.

Stormy Interval - The stormy intervals analyzed had reasonably constant spectral shape characteristics over the interval of significant wave heights used (cf. Table 1). Statistics for the nondimensional parameters were compiled based on the values accumulated for each block of data within each stormy interval.

Composite Statistics - The results from each stormy interval were combined by area, spectral characteristic (such as bandwidth parameter), water depth or other combinations of data. These are the results that are presented in this paper. In all, approximately 148,000 zero-crossing waves were processed digitally and their statistics accumulated. The results presented below are broadly divided into three categories: surface deviation statistics, individual wave height statistics, and individual wave period statistics.

SURFACE DEVIATION STATISTICS

The non-Gaussian behavior of surface deviations are water depth dependent. Jahns and Wheeler [4] demonstrated that fact with shallow water storm wave records obtained in the Gulf of Mexico. For the data available there is no important non-Gaussian behavior discernible in water depths greater than about 350 ft. However, imperfections in the wave measurement systems utilized could easily mask the small deviations that are expected in these water depths. The non-Gaussian behavior of the sea surface manifests itself as a surplus of rare wave crests and a deficit of rare wave troughs relative to those predicted by the theoretical developments of Cartwright and Longuet-Higgins [3]. For the case of zero-crossing waves only, the rare crests (large η^*/σ) are predicted to follow the Rayleigh distribution.

Jahns and Wheeler [4] suggested a correction to the Rayleigh distribution in the following form.

$$P\left[\text{ wave crest } \eta_c \leq \eta^* \,|\sigma\right] = 1 - \exp\left\{-\frac{1}{2}\left(\frac{\eta^*}{\sigma}\right)^2\left[1 - B_1\frac{\eta^*}{d}\left(B_2 - \frac{\eta^*}{d}\right)\right]\right\} \quad (1)$$

This correlation is shown in Fig. 3 along with the composite shallow water data presented by Jahns and Wheeler [4] and Gulf of Mexico data from hurricane Camille in 340-ft water depth [13]. The form of this correlation suggests that the probability of rarely occurring crest heights relative to the storm wave record σ will increase gradually with increasing crest height-to-water depth ratio (η^*/d) and reach maximum near 0.3. The parabolic form of the correlation reflects the fact that crest heights of breaking waves will be about 0.55-0.60 of the water depth. Thus, the water depth effect cannot continue indefinitely with increasing η^*/d.

Another aspect of surface deviation analysis relates to commonly used methods for estimating the fundamental wave record property σ from an instrumentally-recorded analog wave record. It is often not convenient to digitize and process a large volume of analog wave surface deviation recordings from wave measuring instruments. Two methods are evaluated as part of this study. The mean-rectified deviation is easy to record electronically [14]. This recording procedure was simulated using the digitized storm wave data available. Tucker [15] proposes a method that utilizes the highest crest and lowest trough (or second highest crest and second lowest trough) in an analog wave record. These parameters can often be determined quickly by inspection of a paper chart record of 100 or so waves. This procedure was also simulated digitally.

The equations that apply are found in the paper by Tucker [15]. His equations can be rearranged to provide the following estimates of the RMS surface deviation σ of the wave record, σ_r, σ_1, and σ_2, based on the mean-rectified deviation and Tucker's definition of H_1 and H_2, respectively.

$$\sigma_r = \overline{H}_r \sqrt{\pi/2} \tag{2}$$

$$\sigma_1 = H_1/[2\sqrt{2\theta}\ (1 + 0.289\ \theta^{-1} - 0.247\ \theta^{-2})] \tag{3}$$

$$\sigma_2 = H_2/[2\sqrt{2\theta}\ (1 - 0.211\ \theta^{-1} - 0.103\ \theta^{-2})] \tag{4}$$

For each block of wave data, the three estimates of σ were calculated and used to normalize the true σ of the wave record. The mean and coefficient of variation of the accumulated ratios were determined. These results are presented in Table 2.

Table 2. Estimates of RMS Surface Deviation

		σ/σ_r	σ/σ_1	σ/σ_2
Range for 4 Areas (Table 1)				
	Mean	0.997-1.018	0.996-1.028	0.997-1.026
	Coefficient of Variation	1.0-1.4%	8.5-10.1%	5.6-6.6%
Composite Data				
	Mean	1.001	1.011	1.013
	Coefficient of Variation	1.3%	8.7%	6.1%

It is evident from the results that all three methods on the average give an essentially unbiased estimate of the true RMS surface deviation. However, the method based on mean-rectified wave height produces a much smaller coefficient of variation. The relatively large coefficients of variation obtained for the H_1 and H_2 methods could cause significant error in the estimate of σ (and hence of the spectral estimate of significant wave height $H_s = 4\ \sigma$) by infrequent sampling of analog wave records. These errors would compensate over a long time period such as is the case when processing ambient wave statistics. Isolated, severe storm wave records could have true values of H_s substantially different than those assigned by infrequent sampling of the wave record by the H1 or H_2 method.

INDIVIDUAL WAVE HEIGHT STATISTICS

Proper assessment of individual wave height statistics requires that a consistent definition be adopted for wave height determination. As indicated in Fig. 4, wave height can be defined as the difference between the trough and crest elevation between two successive zero crossings in either the upward direction or in the downward direction. One can also assign a wave height based on the average trough depths about a given crest. Of course, the idealized waves assumed in design practice are symmetric about the crest unlike most large rare waves in a storm sea state. The rare wave heights for all possible wave height definitions were normalized to σ and compared with the commonly accepted Rayleigh distribution. These results are presented in Fig. 5. This analysis is concentrated on the highest 1/10th waves which are in excess of the nominal significant wave height $H_s = 4\ \sigma$ for the sea state. The probability of exceeding rare waves on the order of twice the significant wave height was consistently much less for the instrumental storm wave records analyzed than predicted by the Rayleigh distribution. This finding contradicts many publications which assume wave heights are approximately Rayleigh distributed. However, those assumptions are not based on detailed examination of the extreme right-hand tail of data.

A commonly accepted practice for estimating the maximum wave height in a storm sea state is to derive the wave which would be exceeded on the average once in N_z zero-crossing waves. This is given by the following well-known expression:

$$H_{max} = H_s\sqrt{\frac{1}{2}\ \ell n\ N_z} \qquad (5)$$

which can be derived from Equation 3 for large N_z. Table 3 shows the height actually exceeded based on all the normalized storm wave records (Figure 5) relative to the height that is predicted to be exceeded by the Rayleigh distribution (Equation 5) for the probability level of 1 in 1000 waves.

TABLE 3 Compensation of Rayleigh Height Statistics

	$\frac{\text{H Actual}}{\text{H Rayleigh}}$, for $P[H^*\|\sigma] = 0.999$		
	Downcrossing	Upcrossing	Average
Range for 4 Areas (Table 1)	0.87-0.92	0.89-0.94	0.86-0.92
Composite Data	0.892	0.920	0.867

The results are consistent for all areas from which data are available and show on the average the true rare wave height is about 10 percent less than predicted at the 1 in 1000 probability level. The form of the composite statistics shown in Fig. 5 suggests a linear compensation to the Rayleigh distribution as follows.

$$P[\text{wave height } H \leq H^*|\sigma] = 1 - \exp\left\{-\frac{1}{8}\left(\frac{H^*}{\sigma}\right)^2 \left[C_1 + C_2\left(\frac{H^*}{\sigma}\right)\right]\right\} \tag{6}$$

Thus, the exceedance probability for increasingly rare nondimensional wave heights H^*/σ will increasingly depart from the Rayleigh distribution. The extreme wave heights could be renormalized to the true significant wave height ($H_{1/3}$) as measured by the highest one-third waves in the wave records. Of course, the data would then agree with the Rayleigh distribution at a height equal to the significant wave height. However, there would still be a downward compensation of the true wave height distribution relative to Rayleigh statistics required for increasingly rarer waves as a consequence of Equation 6. Furthermore, the true significant wave height $H_{1/3}$ is not necessarily equal to the fundamental property of the wave record, $H_s = 4\ \sigma$. Only $\sigma = \sqrt{m_0}$ is predicted by spectral wave models, and is related to the energy content of the sea surface. Therefore, the most useful scaling parameter for individual wave height statistics would be based on the wave record RMS surface deviation σ as shown in Fig. 5.

INDIVIDUAL WAVE PERIOD STATISTICS

The design engineer must also estimate the zero-crossing period associated with a design wave height. The kinetics of water particle motion in space and time calculated for design waves can vary significantly with wave period. It is also necessary to estimate the zero-crossing period of all waves so that the number of waves per hour for the duration of a nominal storm sea state can be estimated. If the storm wave spectra were extremely narrow-banded ($\varepsilon = 0$), then all wave periods should be essentially equal to the dominant spectral period. Therefore, it is intuitive that the deviations from this ideal situation should be dependent on the bandwidth parameter ε. The definition of ε which we use is based on the ratio of the number of zero-crossing waves to the total number of double-amplitude waves in the block of wave data N_z/N_w.

$$\varepsilon = \sqrt{1 - (N_z/N_w)^2} \tag{7}$$

This is a more stable estimate of ε because it does not depend on the higher spectral moments, which depend strongly on the higher frequency energy and which are subject to some uncertainty due to wave recording and digitization procedures. This subject has been treated in detail by Goda [16].

Figure 6 illustrates the average zero-crossing period normalized to the dominant spectral period over each stormy interval versus the average bandwidth parameter ε for that interval. The results, while empirical, provide a useful correlation to relate the average number of zero-crossing waves in a storm wave record to the bandwidth. Figure 6 shows that even for relatively narrow-banded storm spectra the zero-crossing periods will average about 0.8 of the dominant spectral period. The standard deviation of the ratio T_z/T_d between individual blocks of wave data within a stormy interval is 0.071.

A similar correlation is shown in Fig. 7 for rare wave zero-crossing periods. Here the rare wave period definitions are the average of the downcrossing periods of the highest one-third waves, of the highest one-tenth waves, and of the maximum wave in the particular block of wave data. The same trend is exhibited for all of the large well formed waves in a storm sea state. This confirms results reported by Goda [16]. Consequently, we can conclude that the average period of the significant waves and larger exhibit an essentially constant ratio to the dominant spectral period of the sea state in which they occur. The ratio is less than unity and is bandwidth dependent. This result implies that the extreme wave heights in a sea state are associated with steeper waves of essentially the same zero-crossing periods on the average as the less rare waves in that sea state. Comparison of Fig. 6 with Fig. 7 shows that the average period of the large waves is always greater than the average zero-crossing period of all the waves in the record. As indicated by the dashed lines in Fig. 7, these correlations are not exact. The standard deviation of the wave periods normalized to the dominant spectral period between individual blocks of data increases as the wave rarity increases.

The empirical results presented in Figs. 6 and 7 also can be presented in terms of wave periods derived from properties of each storm sea state spectrum. Formulae have been suggested [1,3,16] for estimating average wave record properties as follows:

$$\tilde{T} = 2\pi\, m_o/m_1 \tag{8}$$

$$T_o = 2\pi \sqrt{m_o/m_2} \tag{9}$$

$$\varepsilon_s = \sqrt{1 - m_2^2/m_o m_4} \tag{10}$$

These formulae should account for finite spectral width ($\varepsilon \neq 0$) by incorporating the higher spectral moments. These spectral estimates were normalized by their corresponding true values for each block of data and compiled over each stormy interval analyzed. These results are presented in Figs. 8 and 9 versus the bandwidth parameter. The spectral estimates consistently underpredict the true values of wave period as derived from the wave records, particularly for the wider-banded wave spectra. Note that the standard deviation of the normalized ratios is substantially less than for the results shown in Figs. 6 and 7. There is no consistent correlation between the spectral estimate ε_S with that derived from the wave counts. On the average the spectral estimate of bandwidth parameter ε_S is about 5 to 15 percent greater than the value defined by Equation 7 for the storm wave records analyzed.

CONCLUSIONS

1. The properties of storm waves that are rare in their sea state show uniform, correlatable behavior when nondimensionalized by the fundamental spectral properties derived from the wave records. This result covers a wide range of geographic locations, water depths, and storm characteristics.

2. Surface deviation statistics are non-Gaussian and exhibit a surplus of rare crests relative to the Rayleigh distribution out to at least 340-foot water depth as determined by hurricane Camille wave records from the Gulf of Mexico.

3. Simplified methods to estimate the true RMS surface deviation σ of a storm wave record are unbiased on the average, but some methods can lead to substantial error when applied to a small sample of wave record.

4. The statistics of extreme wave height, as measured by elevation difference between trough and crest, deviate substantially from the Rayleigh distribution at the 1 in 1000 wave probability level. The true observed wave heights are on the order of 10 percent less than predicted.

5. The zero-crossing wave periods for the entire record and for the rare waves in a sea state can be nondimensionalized by the dominant spectral period and correlated with bandwidth parameter ε. The wave periods relative to the dominant spectral period decrease as bandwidth increases.

6. The approximate formulae for individual wave periods and bandwidth parameter based on higher spectral moments do not agree well with results obtained directly from the wave records.

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NOMENCLATURE

B_1, B_2 = arbitrary constants (Equation 1)

C_1, C_2 = arbitrary constants (Equation 6)

d = water depth

f = frequency, Hertz

$\hat{h}$ = dimensionless wave height, H/σ

H^* = arbitrary wave height

H_{max} = estimate of maximum wave height (Equation 5)

$H_{1/N}$ = average height of highest 1/Nth waves

$\bar{H}_r$ = mean-rectified wave height

H_s = $4\sigma = 4\sqrt{m_o}$ = spectral estimate of significant wave height

H_1 = Wave height based on highest crest and lowest trough in wave record

H_2 = wave height based on second highest crest and second lowest trough in wave record

m_k = kth moment of amplitude energy density spectrum (Figure 1)

N_z = number of zero-crossing waves in wave record

N_w = number of double-amplitude waves in wave record (number of crests)

P[] = probability that statement in brackets is true

T_d = $1/f_d$ = dominant spectral period

$T_{1/N}$ = average zero-crossing period of highest 1/Nth waves

T_{max} = period of highest wave in wave record

T_o = spectral estimate of average wave period (Equation 9)

T_z = average zero-crossing period in wave record

$\tilde{T}$ = spectral estimate of significant wave period (Equation 8)

γ = dimensionless crest height, η_c/σ

Δt = time interval between digitized wave record points

ε = bandwidth parameter (Equation 7)

ε_s = spectral estimate of ε (Equation 10)

η_c = crest height of zero-crossing wave

η^* = arbitrary crest height above mean water level

ω = circular frequency

σ = RMS surface deviation of wave record

$\sigma_{r,1,2}$ = estimates of σ (Equations 2, 3, 4)

θ = $\ell n\ N_z$

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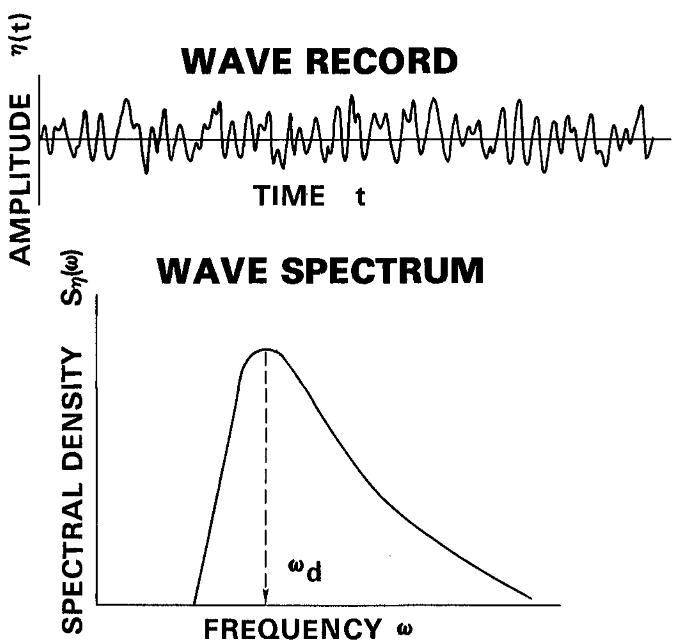

DERIVED PROPERTIES

$m_K = \int_0^\infty \omega^K S_\eta(\omega)\, d\omega$, THE Kth SPECTRAL MOMENT

$T_d = 2\pi/\omega_d$, THE DOMINANT SPECTRAL PERIOD

$\sigma^2 = m_o$, THE VARIANCE OF WAVE RECORD $\eta(t)$

Figure 1. Typical sea state spectrum

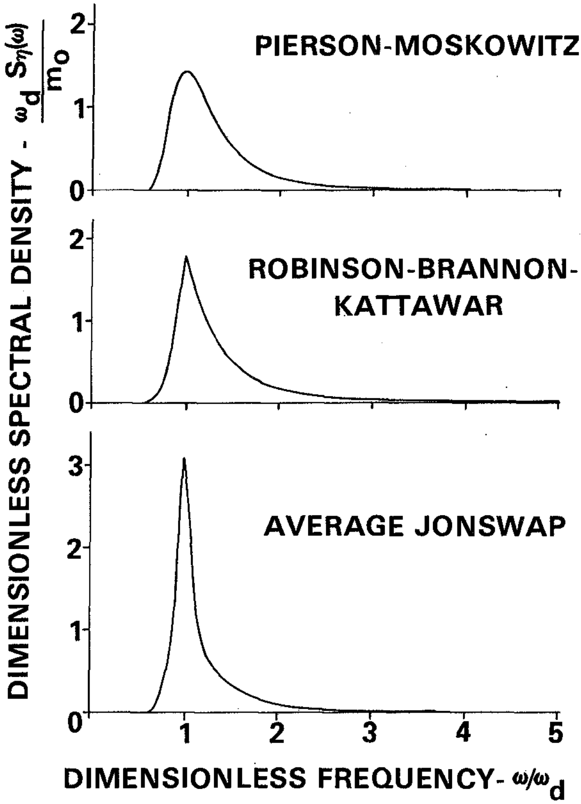

Figure 2. Model spectral shapes

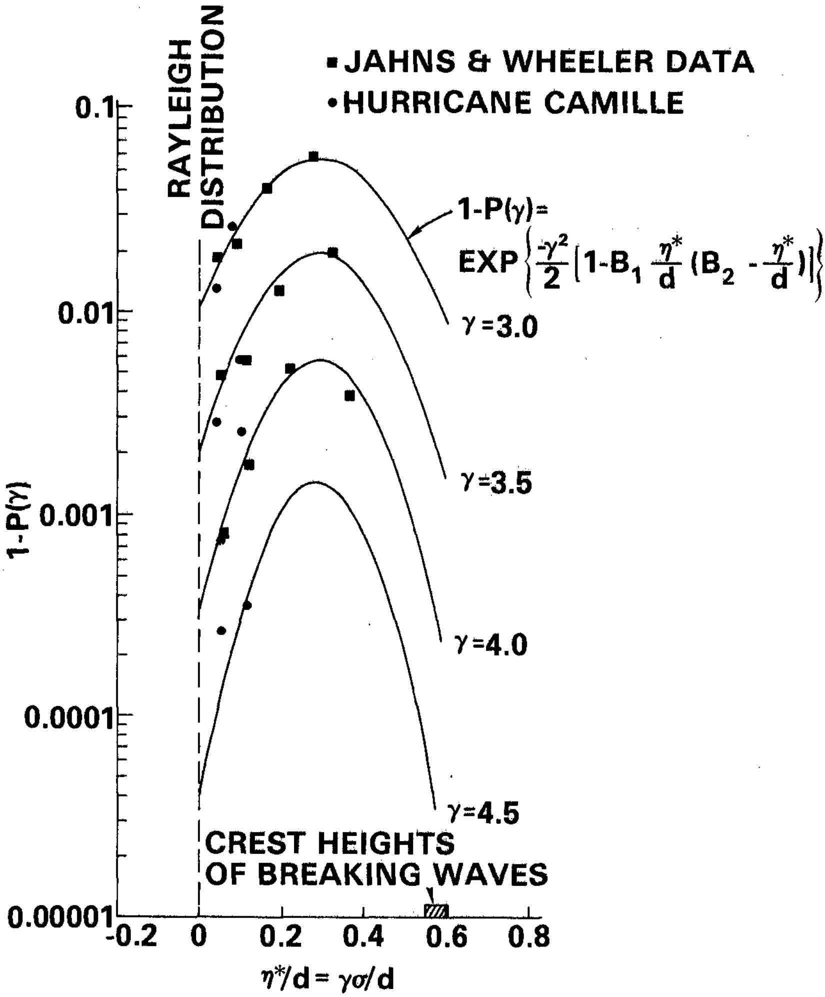

Figure 3. Rare wave crest statistics

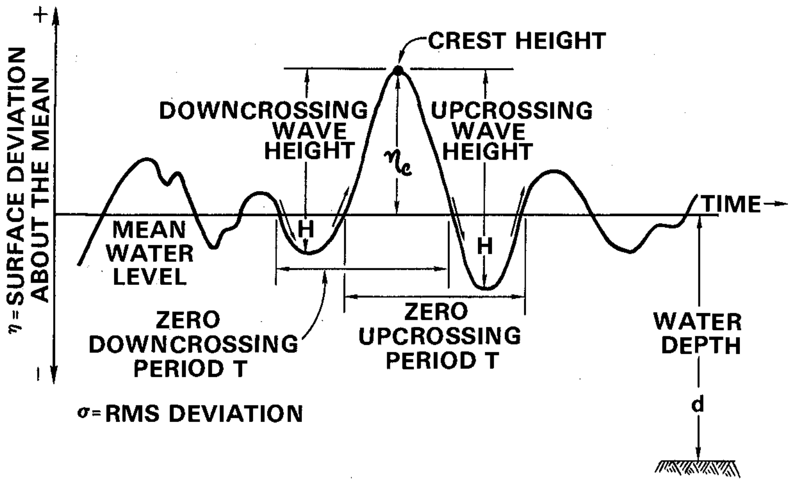

Figure 4. Wave height definitions

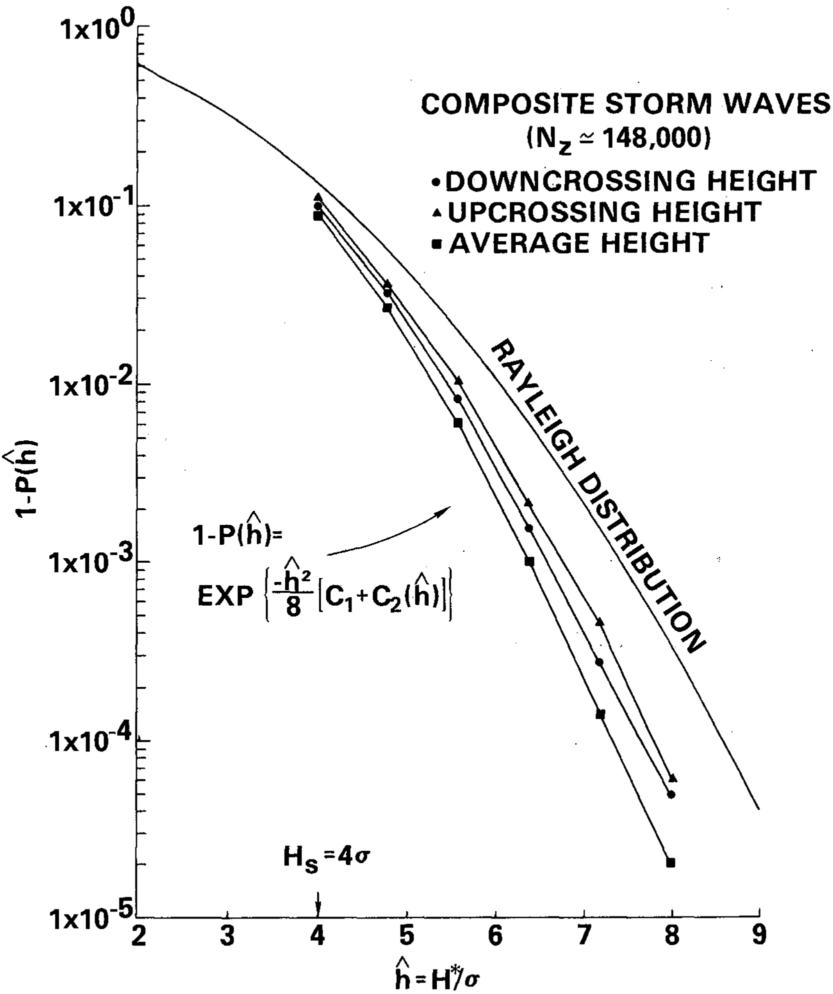

Figure 5. Rare wave height statistics

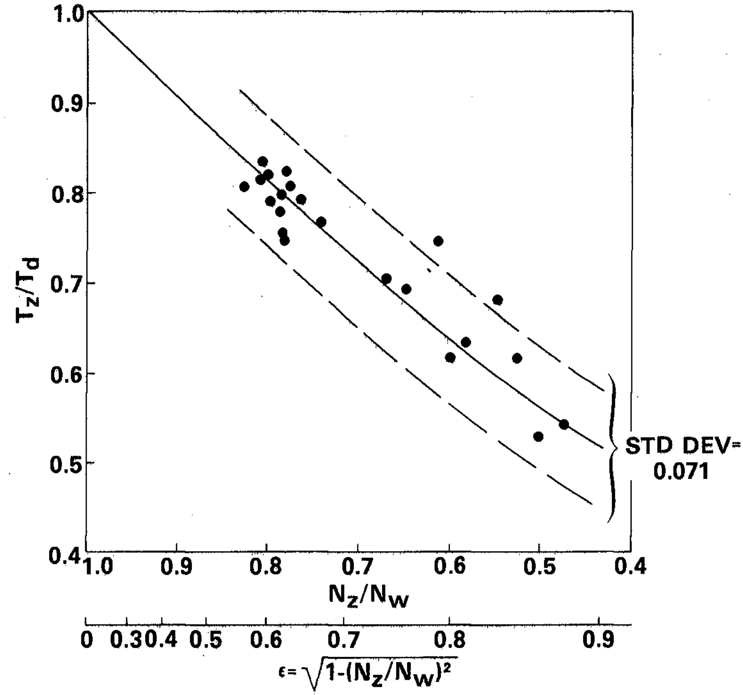

Figure 6. Average zero-crossing period

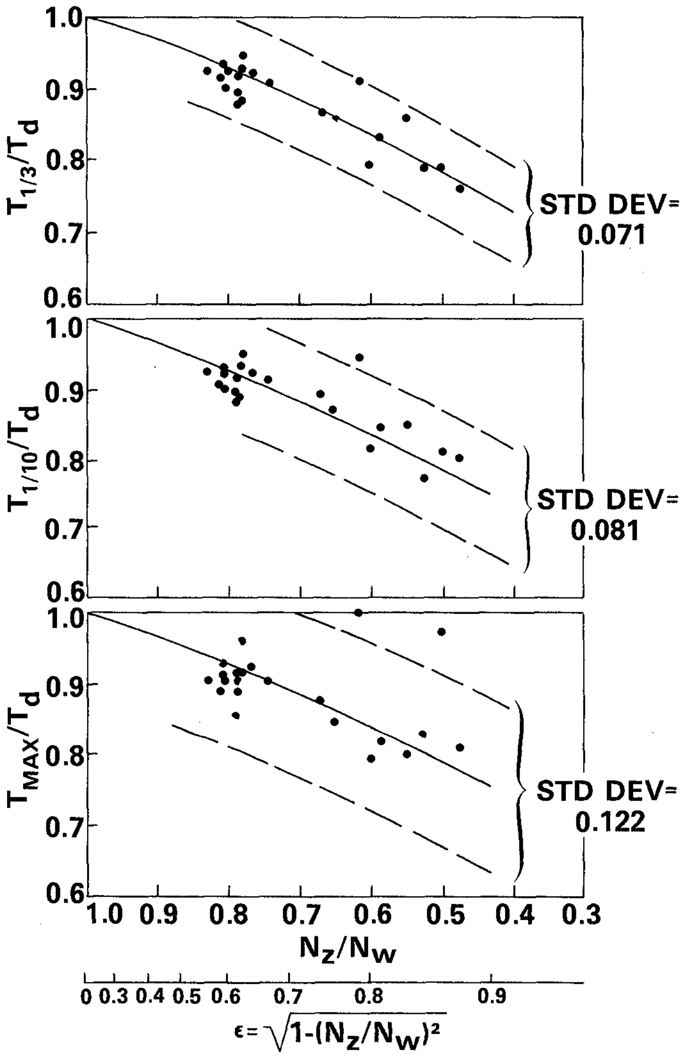

Figure 7. Rare wave periods

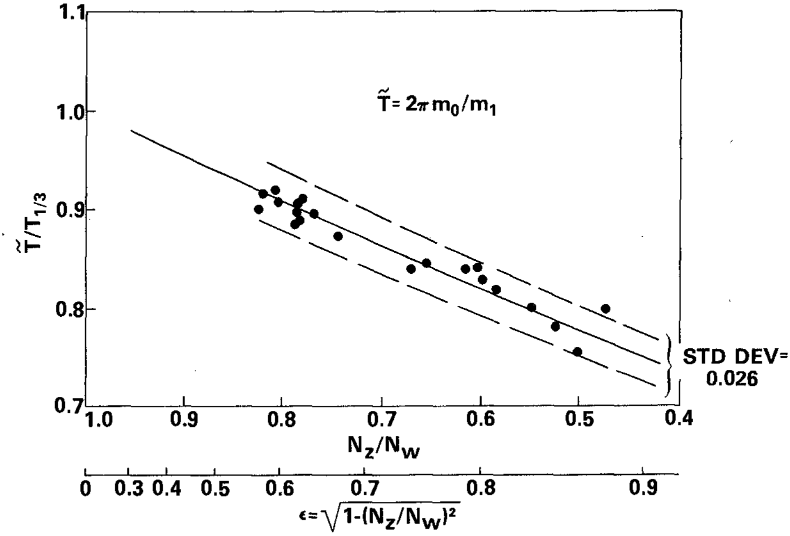

Figure 8. Spectral estimates of wave period

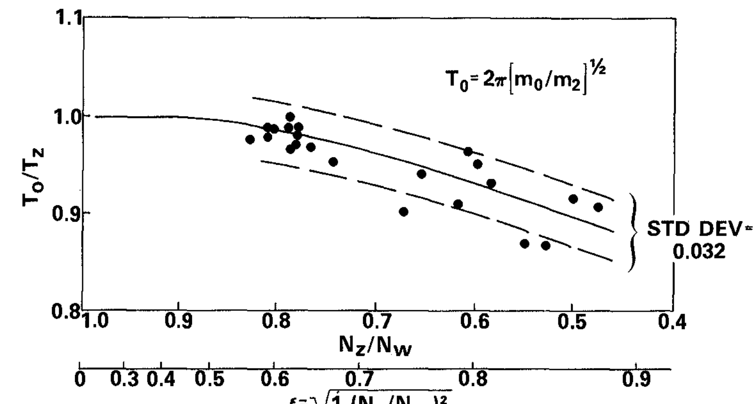

Figure 9. Spectral estimates of wave period