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WAVE STATISTICS BASED ON SHIP'S OBSERVATIONS

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ABSTRACT

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Wave observations made visually from selected ships are commonly used in coastal engineering for design purposes. The reliability of wave statistics based on ship's observations appears to be acceptable provided a large number of observations is available and the maximum observed waves are considered with care.

A computer program was developed to process data from magnetic tapes made available by meteorological offices. Exceedance frequencies, wave roses and wave power distributions can be computed both for deep-water and shallow-water conditions. Littoral drift and return periods of extreme wave conditions are computed as well.

Some results are presented for the southwestern part of the French Mediterranean coast.

INTRODUCTION

Wave statistics are required in various fields of coastal engineering such as: coastal morphology, for computation of the littoral drift capacity under oblique wave action; structural design, for computation of the design wave conditions; harbour layout, for computation of the wave penetration.

Wave statistics can be obtained in various ways. One can install wave-measuring devices on the spot where information is needed; this will yield data which, if processed adequately, may provide energy density spectrums. However, major problems arise due to vulnerability of the measuring devices (30—60% downtime, generally during the more interesting stormy seasons) and the short registration periods which have no real statistical value.

Another method consists of mathematical simulation of selected storms based on weather charts. An advantage is that meteorological data are generally available over longer periods than wave data. However, this promising method is still quite expensive due to high computational costs and the large number of storms to be simulated to obtain data with any statistical value.

The most commonly method used is based on wave observations made

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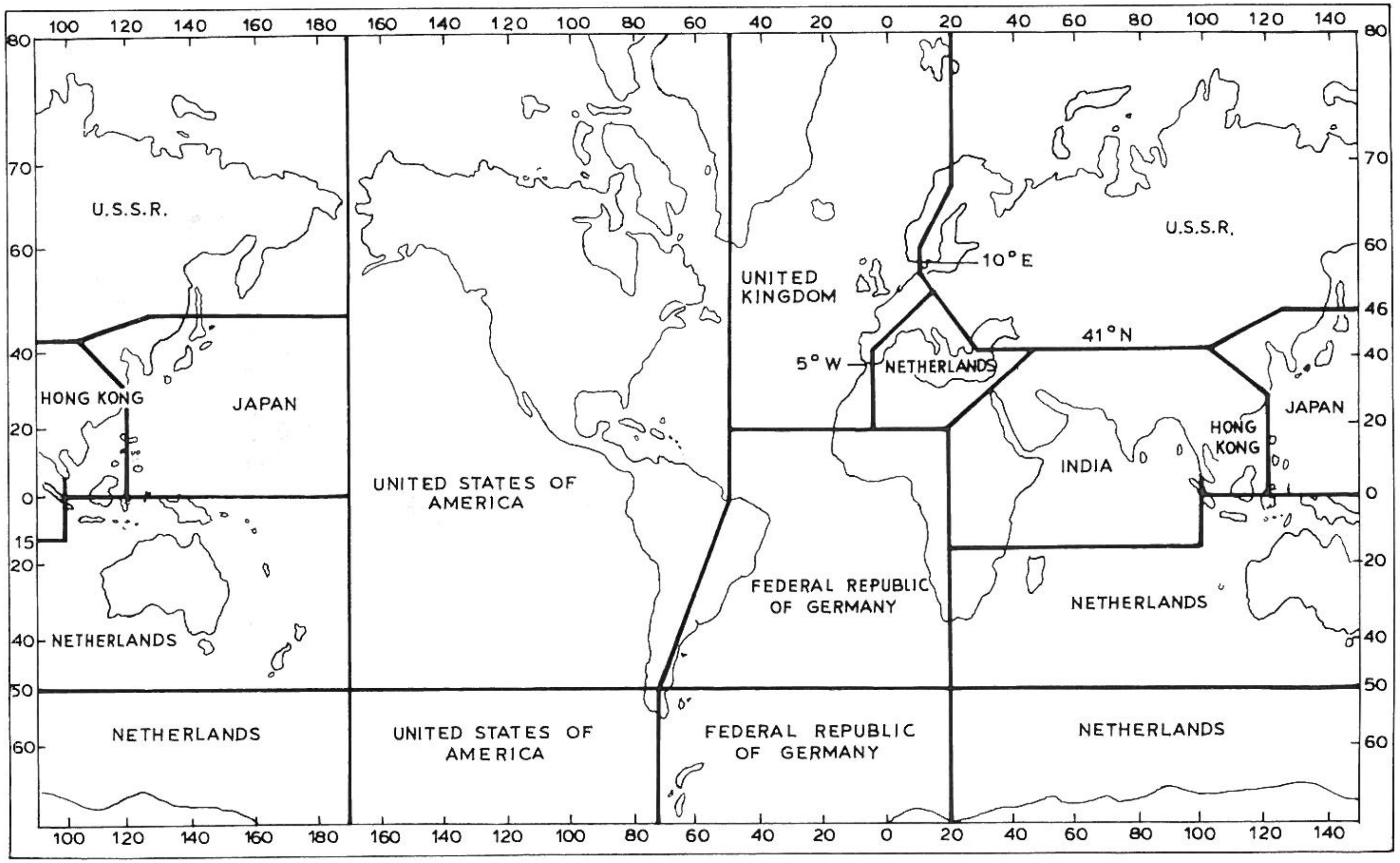

Fig. 1. Areas of responsibility for marine climatological summaries.

visually from selected ships. Much data have been collected in the seas around the world, especially in the sixties and seventies. However, the simplicity of the observation means yields some inaccuracies.

In the following sections, we shall go further into the various aspects of wave statistics based on ship's observations and try to find out how to use these data efficiently.

WAVE OBSERVATION AND DATA PROCESSING

A fundamental distinction is made between "sea" and "swell". The first being waves observed within the generating wind field, and the latter being waves observed outside the generating area.

Distinction by observers is deduced from the definition above. So, seas travel in the direction of wind, while swell may occur from other directions. However, if swell occurs from the wind direction, distinction between sea and swell is more difficult and mostly based on wave periods, assuming the periods of swell are longer.

Wave periods and directions are measured with simple means such as compass and stopwatch which lead to a fair estimate. However, the moving of the ship yields some inaccuracies.

It should be noticed also that observation of swell with periods larger than 13 s is extremely difficult.

Estimates of wave heights are more subjective and can only be performed by very experienced observers.

Observations are recorded by means of a code in which wave heights are expressed in half meters, directions in tens of degrees and periods classified into classes of one or two seconds.

Data collected by ships are transferred to the meteorological office responsible for data processing in each area (Fig. 1).

For instance, Great Britain is responsible for the North Sea (about 0.5 million observations from 1961 to 1980) and for the North Atlantic Ocean (about 6 million observations from 1961 to 1980) and the Netherlands are responsible for the Mediterranean sea (1.7 million observations from 1961 to 1980). The American National Climatic Center (NCC) collects data from all over the world.

Data are made available by the various meteorological offices either processed or unprocessed. Processed data include numbers of observations as a function of wave height and period for the various directions and seasons. This is the most comprehensive way of presenting data, as was done by Hogben and Lumb (1967) (by the way, remember the +30 degrees correction on their directions, see Hogben and Lumb, 1974). However, in most cases, data have to be reprocessed to fit the coastal engineer's aims.

For this reason, it is worthwile to mention that unprocessed data are also made available on magnetic tapes which contain the observed wave conditions for each observation.

A 2400-ft tape (6250 bpi) may contain up to one million observations and can be purchased for 100 to 200 US Dollars (1984) (US, the Netherlands, France). However, the British meteorological office sells its data for a so-called "commercial" price of about 10 US Dollars (1984) per thousand observations.

The author observed that the quality of the Dutch and French data was very good, apparently carefully checked. More erroneous wave data were found in the American data, at least in one application on the West African coast. It was observed furthermore that Dutch delivery was performed within ten days, but that the French and Americans required several months (1984).

RELIABILITY OF WAVE OBSERVATIONS

Considering the fact that wave periods may be estimated quite accurately by means of a stopwatch, the question of reliability of visual wave observations concerns mainly wave heights.

It should be reminded first that the original definition of the significant wave height was chosen because it fitted fairly the visual estimate of a trained observer (H_s = average of the one-third highest waves).

A number of checks are reported in the literature and among them, the recent check performed by Jardine (1979) in the North Atlantic Ocean. He compared the significant wave height from a shipborne wave recorder with visual observations made aboard the same weather ship. He found 3901 cases where there was both a measured and an observed wave height.

According to Jardine, the best fit line is given as (H_v and H_m, visual and measured wave heights in meters):

$$H_v = 0.022\, H_m{}^2 + 0.78\, H_m + 0.83 \qquad (1)$$

which may be approached by:

$$H_v = H_m + 0.5 \qquad \text{for } H_v \leqslant 5 \text{ m} \qquad (2)$$

$$H_v = 1.10\, H_m \qquad \text{for } H_v > 5 \text{ m} \qquad (3)$$

A few comments are to be made:

(a) The scatter of data is very large, which means that valuable comparisons between measured and observed wave heights can only be performed with large amounts of data.

(b) Observed wave heights seem to be 0.3—0.8 m larger than measured values (as an average) for $H_v \leqslant 5$ m, and are 10% larger than measured values for $H_v > 5$ m (eqs. (2) and (3).

Jardine reports a possible under-estimation of the measured low wave heights ($H_m < 1$ m) due to its electromechanical characteristics. Furthermore, it may be assumed it is "human" to overestimate observed very high waves.

(c) In other checks than that of Jardine, the problem arises of the selected area in which the ship's observations are taken. If it is too small, it will not provide enough data, and if it is too large, it may contain irrelevant data from a different climatic area. However, this problem does not arise in Jardine's check since both observed and measured values were taken from the same ship.

Concluding this section, it is assessed that average observed wave heights give a fair estimate of significant wave heights by means of eqn. (1) provided a large number of observations is available. Furthermore, observations of very large waves should be considered very carefully from a statistical point of view; this concerns especially wave heights which were not exceeded more than 10 times during the observation period (see also section on "Extreme wave conditions").

DATA PROCESSING FOR COASTAL ENGINEERING PROBLEMS

SOGREAH has recently developed a computer program (HOULROSE) to process data according to the coastal engineer's needs. The program allows for several checks of the data: selection of extreme wave heights, periods, wave steepnesses, number of observations with one or more undetermined parameters, sea states observed more than once at the same time, geographical positioning of observations, etc. A few examples of results from this program will be given hereunder. The data is taken from a study performed for the southwestern French Mediterranean coast (42.5 to 43.3 degrees North and 3.5 to 5.5 degrees East where 15,782 wave observations were performed between 1.1.61 and 31.12.80).

Wave rose

This is the most concentrated way of presenting the data since the exceedance frequencies of only a few wave heights are given as a function of direction (which may be represented by sectors of 10 degrees or more, Fig. 2).

The rose consists of logarithmic scales from 1 at the centre to 10^{-5} at the outer circle, and reproduces exceedance frequencies.

Such a rose can be set up either for sea or for swell. Since both wave types may be considered but are observed simultaneously, the combined occurrence frequencies can be based on simple probabilistic rules.

Statistics are often made for a sector of interest of about 180 degrees (case of a straight coastline). Offshore wave observations which do not fall within the sector of interest are read as "calms" to obtain sea conditions near the continent.

The wave rose provides a first appraisal of wave conditions, especially dominant wave directions. It is also a useful tool for comparing statistics in various sites or for various selected observation areas.

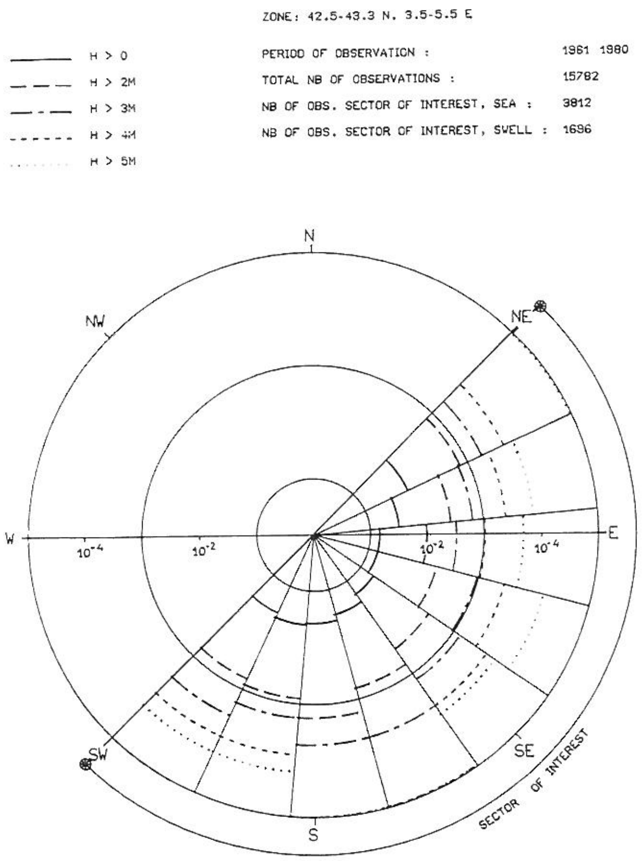

Fig. 2. Wave rose. Sea and swell offshore. Occurrence frequencies related to total number of observations.

However, a shortcoming of the wave rose is that it does not take into consideration wave periods and does not allow extrapolations.

Wave power

The wave power is computed per unit of crest length, and is proportional to H^2T according to the linear wave theory (T is deep water wave period).

The value of $\Sigma n\ H^2T$ is computed for each selected direction, n being the number of observations for each pair of wave height (H) and wave period (T). The absolute values of the wave power are of little interest since they depend on the number of observations; more interesting are the relative values as they yield dominant directions (Fig. 3a) and dominant periods (Fig. 3b).

The wave power distribution provides a first appraisal of littoral drift directions and is a useful tool in selecting wave directions and periods for refraction and wave penetration computations.

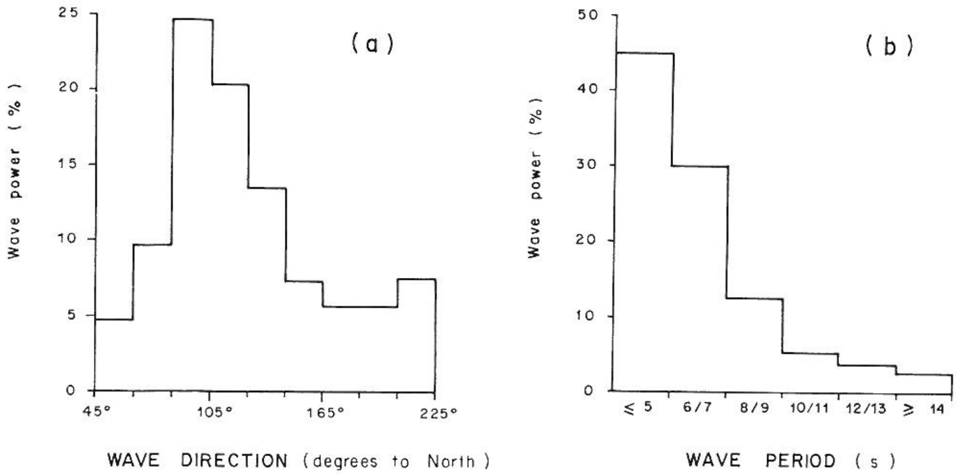

Fig. 3. Wave power distribution: (a) H^2T versus direction; (b) H^2T versus period.

Nearshore wave statistics

Assuming wave observations made by ships are characteristic for deep water waves, the coastal engineer will, in many cases, not be satisfied as he needs statistics in shallow water (for example for breakwater design) or even at the breaker zone (for littoral drift computation).

Waves may be refracting and/or diffracting on their way to shallow waters and a number of tools exist to estimate the changes in wave height and wave direction.

The HOULROSE program provides a possibility to introduce these changes as a function of wave direction and period.

This conversion from offshore to nearshore statistics is a major feature of the program as one may think of the tremendous work this represents if it was to be done by hand.

Littoral drift

Littoral drift can be computed if wave conditions at the breaker zone are known. As a matter of fact, a transport capacity is found which may be different from the actual littoral drift; in that case, the coastline is not stabilized (erosion or sedimentation).

Many formulae are available for computation of littoral drift, but the best known and simplest is the formulae of CERC (1984):

$$S = A\, H_o^2\, K_r^2\, C_o \sin\phi_b \cos\phi_b \quad (4)$$

where:

S: littoral drift capacity (m^3/year)

H_o: deep-water significant wave height (m)

K_r: refraction coefficient
C_o: deep-water wave celerity (m/s)
ϕ_b: wave incidence at breaking depth (rd)
A: 615,000.
The constant A was chosen as an average between values mentioned in the literature ranging from $A + 30\%$ to $A - 30\%$.

Computations are performed assuming each wave height and wave direction yield an independent contribution to the total littoral drift according to its frequency of occurrence. The results are presented for a given orientation of the coastline with respect to North and a sensitivity analysis is performed for several slightly different orientations. Littoral drift is indeed very sensitive for coastline directions. This is a well known fact which means that littoral drift computations are only meant to give a rough estimate.

Extreme wave conditions

The program can select observations with a wave height greater than a given value. This is useful from a historical point of view, but it has no value from a statistical point of view as this generally concerns a very limited number of observations.

The problem thus arises how to describe extreme wave conditions. Obviously by some kind of extrapolation by means of a distribution which would be valid both for average and for extreme wave conditions. Unfortunately, none of the presently existing distributions has been proved to be absolutely reliable.

For the time being, we can only choose a few distributions and compare the results (Fig. 4a).
Semi-logarithmic distribution:

$$Pr(H > H_i) = 10^{(H_i - H_o)/A} \qquad (5)$$

Two-parameter Weibull distribution:

$$Pr(H > H_i) = \exp[-(H_i/H_o)^A] \qquad (6)$$

The regression curves were computed by means of a weighted least-squares method in such a way that the weight of each point in Fig. 4a equals the number of exceedances corresponding to each point. Hence, extreme wave conditions which are exceeded a few times only during the period of observation have a very small influence on the resulting regression curve.

Furthermore, wave heights less than 1 m are not taken into account since they generally belong to a different distribution and would have a large influence on the resulting regression curve because of their "weight".

The upper limit of the 80% confidence interval is computed according to Le Méhauté's formula (1983), and is presented in Fig. 4 as a 90% no exceedance confidence limit.

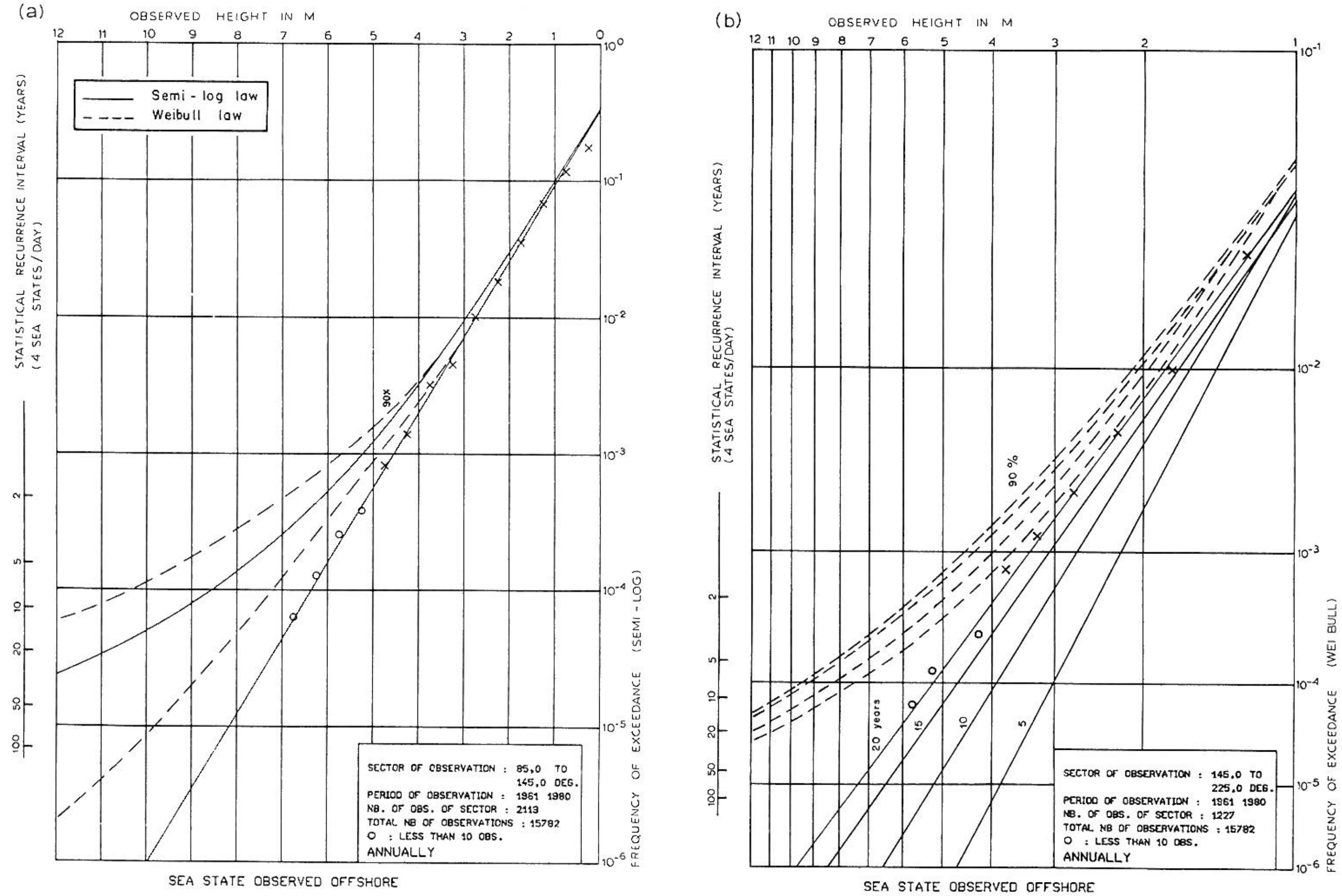

Fig. 4. Exceedance probabilities: (a) Comparison of Weibull and semi-log distributions. (b) Comparison for various observation durations.

It can be observed in Fig. 4a that both distributions agree quite well with average wave conditions, that is for wave heights observed many times.

Wave heights that were exceeded less than 10 times do not fit the Weibull distribution very well, but fit the semi-log distribution. However, this conclusion is specific to the case reported in Fig. 4a (sector of directions North 85° to North 145°).

It appears from Fig. 4b that the Weibull distribution leads to better results for another sector of directions (N145° to N225°). Hence, preference for either one of both distributions cannot even be related to a geographical area, but is also depending on distribution directions.

Figure 4b shows regression lines based on 5, 10, 15 and 20 years of observation, that is on respectively 340, 667, 1001 and 1227 observations of waves in the considered sector of directions. The increase of the slope of the regression line with the number of years of observation is striking and obviously not stabilised with 20 years of observation (1227 observations). However, stabilisation of the slope was found for less than 1000 observations in another case.

For the time being, it may be carefully concluded that at least 1000 to 1500 observations are required for each selected sector of directions to provide a fair estimate of long-term statistical distributions of wave heights. This implies that selection of sectors should be performed accordingly and that sectors of 10° may be too small in many cases: if a 180° sector of interest is considered and subdivided into 6 sectors of 30° each, at least 6000 to 9000 observations are required.

This conclusion may not be disconnected from the requirements deduced from Le Méhauté's computations, i.e. the duration of observation (in years) should not be less than 25% to 40% of the considered design return period (in years).

DESIGN WAVE CONDITIONS

At this stage, we leave the field of observation of the past, to enter the field of forecasting the future.

TABLE 1

Extreme wave conditions (sector of directions: N85 to N145)

Exceedance probability	Wave height (m)	
	Semi-log	Weibull
10^{-4}	6.4	7.2
10^{-5}	8.2	9.8

Extrapolation

Extrapolation to extreme wave conditions in Fig. 4a leads to the results shown in Table 1. Other comparisons, such as reported by Mynett et al. (1983) for Sines (Portugal) suggest the same kind of differences between four laws (Fisher-Tippett I, linear and squared Gumbel, three-parameter Weibull): differences do not exceed 3%, 6% and 9% for design waves with return periods of 10, 50 and 100 years respectively.

Return period

It has become common practise to express the probability of occurrence of extreme events in terms of statistical return periods. This means a conversion of exceedance probabilities during one observation to exceedance probabilities during one year.

It should be emphasized once more that a probability of 1 in 10 to have a given storm in one year, does not yield a probability of 1 in 1 to have such storm in ten years (this probability is only 65.1%, according to the Poisson distribution); neither does it exclude the possibility of having two of those storms in one year (the probability is still 1%).

The computation of the return period is based on the following assumptions:

(a) Wave observations are assumed to be uniformly distributed in time.
(b) Each wave observation represents one specific sea state.
(c) All sea states are independent from each other.

These assumptions are obviously not valid since (a) wave observations by ships are (at best) random; (b) some sea states may not have been observed, or observed several times; (c) consecutive sea states may not be independent, especially during long storms.

Nevertheless, the assumptions are frequently made to obtain the following conversion formula which can be easily derived from the probability rules:

$$P_o = 1 - (1 - P_a)^{1/n} \tag{7}$$

where:

P_o = exceedance probability (of a given wave height) during one observation (or sea state);

P_a = exceedance probability (of the given wave height) during one year with n sea states;

$1/P_a$ = statistical return period.

A problem arises with the number of sea states during a year (n). Strictly speaking, n should be the number of observations during a year, according to the deduction of eqn. (7). But n is set to the number of sea states according to assumption (b) above. In fact, both quantities should be equal, but this never occurs.

TABLE 2

Return periods

n	P_o (10^{-5}) $P_a = 1/2$	$P_a = 1/5$	$P_a = 1/10$	$P_a = 1/20$	$P_a = 1/50$	$P_a = 1/100$
365	189.7	61.1	28.9	14.1	5.53	2.75
730	94.9	30.6	14.4	7.03	2.77	1.38
1460	47.5	15.5	7.22	3.51	1.38	0.69

The choice of n is delicate. On the one hand, one would like to have n as close as possible to the average number of observations per year. On the other hand, one would like to use a realistic estimate of the average duration of a sea state, e.g. in places with trade winds like in the Mid-Atlantic Ocean, a duration of 12—24 hours (n = 365—730) may be expected, while in places like the North Sea and the Mediterranean Sea, where winds blow seawards in the morning and landwards in the evening, a duration of 6—12 hours (n = 730—1460) seems a better estimate.

Fortunately, the influence of n on the final result concerning the significant wave height of a design storm with a given return period is not too large. Table 3 gives some results deduced from Fig. 4a (semi-log scale).

TABLE 3

Design wave conditions (sector of directions: N85 — N145)

Return period (years):	H_s (m) 20	50	100
n			
365	6.1	6.8	7.4
730	6.6	7.4	7.9
1460	7.2	7.9	8.5

The difference in H_s between two consecutive values of n, does not exceed 0.6 m.

The use of the return period when defining design wave conditions is obviously not as simple as it looks. The definition looses much of its value when basic parameters like number of observations, period of observation and chosen duration of sea states are not mentioned.

UNCERTAINTIES IN WAVE PREDICTIONS

The various sources of errors mentioned in the previous section lead to uncertainties in the computation of the design wave.

The following estimates might be deduced from various sources and ex-

pressed in terms of a standard deviation as a percentage of a design wave with a 50-year return period:
— uncertainty due to observation period of 20 years: σ = 10—15%,
— uncertainty due to observation mistakes: σ = 10—20%,
— uncertainty due to extrapolation law: σ = 5%,
— uncertainty due to long-term climatic changes: σ = 5%.
These uncertainties may be considered independent, so the total uncertainty on the computed design wave may be deduced from the sum of variances. This yields: σ = 15—25%.

Hence, a computed design wave height with a return period of 50 years should be considered as an average with a standard deviation of σ = 15—25% in a Gaussian distribution.

Another, more accurate, way to show these uncertainties is presented in Fig. 4 as a 90% no exceedance confidence limit.

Finally, it should be noticed that, especially in lightly travelled seas, an additional source of uncertainty may be that ships try to avoid bad weather areas, so that the distribution lacks the larger wave heights that should have been there from a statistical point of view.

CONCLUSION

Accurate prediction of extreme wave conditions has become increasingly important as coastal works move to more exposed sites and design safety margins are reduced to tie up construction cost. This is true especially for *breakwater design* in rather deep waters, since these structures are no longer protected from extreme waves by shoals.

A sound knowledge of the wave climate is also required for *littoral drift* computations. As the accuracy of the presently available littoral drift formulae is quite low, one should avoid adding any additional sources of errors in their use.

Computations of *wave penetration* into harbours by means of mathematical or scale-model tests are expensive. Reliable wave statistics are required for a sound selection of wave directions and periods to be taken into account, which is a major issue in reducing the number of tests and the cost. However, it should be kept in mind that, at the present level of knowledge, forecasting of wave climates is not a very accurate science and that computation of a design wave is subject to a standard deviation of 15—25%.

The use of ship's observations is one of the ways to obtain reliable wave statistics. Other methods such as in situ measurements and mathematical simulation of storms are available also, but are more expensive and usually do not (yet) cover a large enough period. For the time being, these methods can be used best as checks on wave statistics obtained from ship's observations; however, future technological progress and investment in wave-measuring systems should enable reversing this procedure.

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