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DETERMINATION OF SEVERE WAVE CONDITIONS FOR OCEAN SYSTEMS IN A 3-DIMENSIONAL IRREGULAR SEAWAY

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by

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1. ABSTRACT

Testing of ocean systems in hydrodynamic laboratories is generally performed by wave attack with either regular or irregular random waves. Whereas many engineers believe that the use of long sequences of random waves for testing purposes offers a high probability that all extreme test conditions will be encountered sooner or later, experience at NHL has indicated that this is not generally the case. Tests with smaller vessels and moored offshore systems have shown, that some critical events in terms of extensive surge, extensive mooring force, extensive acceleration, sliding of cargo or capsizing might occur in deterministic generated large plunging breakers occurring in deep water, when all single wave components contained in a given sea state are focused in a giant wave collision exactly on the ocean system during testing.

The same critical events are not occurring, when the given sea state is simulated in a random way in the laboratory. On the basic of this experience, a new design philosphy is presented that contains a new method for selection, generation and probability evaluation of freak waves occurring either single as large plunging breakers in deep waters, or occurring in random wave trains, in a short-crested 3-dimensional sea.

2. INTRODUCTION

The severe background for the initiation of the study in Norway of extreme wave conditions encountered by small vessels, is the loss of not less than 26 Norwegian vessels and 72 lives in the period 1970 - 79 in Norwegian waters. These vessels were all quite large trawlers and freighters up to 500 GRT with total lengths up to 76 m. Reports from Courts of Inquiry show that for 13 of these vessels, surviving members of the crew confirmed that the vessels capsized due to large breaking waves. In the remaining 13 cases the Courts of Inquiry concluded that the vessels were lost in bad weather without survivors, the reason being unknown but capsizing in extreme seas is the most probable. A sudden capsizing seems to be most probable because no emergency calls were given. In addition to this comes a large number of losses of smaller Norwegian fishing vessels below 40 feet. These vessels usually have a crew of one or two people, but these losses are not recorded in the statistics from Norwegian authorities. A further addition to these statistics are the losses of several large foreign trawlers in Norwegian waters in the same period and finally some losses of pleasure boats and sailing yachts should be included.

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Several large research projects have therefore been performed in Norway in the last few years focusing on the sudden appearance of large near-breaking or breaking freak waves in a given sea state, the consequences in terms of responses for vessels or other ocean systems in the area, the probabilities associated with such events, and finally the precise reproduction of such events in laboratory experiments. From this work performed at the Ship and Ocean Labratory at the Norwegian Hydrodynamic Laboratories a completely new design philosophy has been derived as follows:

1) Select site for installation or operation.
2) Determine design sea state from long term statistics.
3) Determine wave trains containing freak waves that matches combinations of critical periods, directions and dimensions for the ocean system
4) Generate in a deterministic way gravity waves that contains a focusing of wave energy exactly at the ocean system, matching critical periods and appearing as wave trains containing extreme freak waves breaking as plunging breakers in deep waters.
5) Determine from oceanographic measurements the statistical probabilities for occurrences of the simulated test conditions.
6) Measure the extreme response in an experiment.
7) Observe if a critical event occurs and repeat the experiment.
8) Give the probability for failure of the design, see Fig. 1.

Design philosophy:

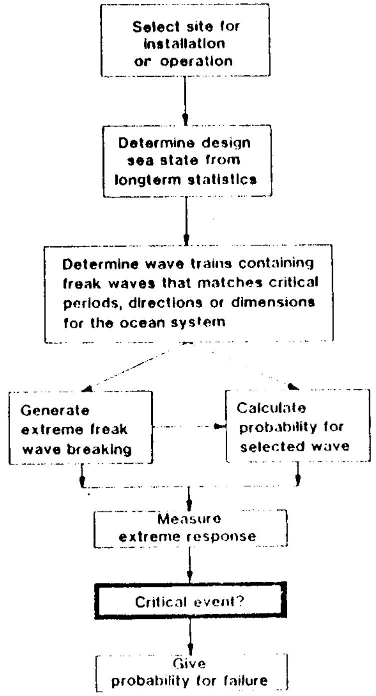


Fig. 1. Design philosophy.

A matter that always intrigues us is the occasional appearance of an extra mountainous wave encountered by a ship, a wave out of all proportion to the others in the area. Since the sea surface is apparently the sum of a multiplicity of simple wave systems, it will be enlightening to learn what will be the result of a concurrence of all crests of an assumed set of wave systems, the time probability of such an event and the response of a ship under way in the area. After all we must provide for the worst.

This philosophy was first derived in a research programme "SHIPS IN ROUGH SEAS" (see publication from NSFI/RINA (1982)), but has now obtained much more international attention, and have recently been used in two projects performed for the offshore industry with experimental simulations performed at the Norwegian Hydrodynamic Laboratories. The same kind of philosophy might very well be applied to coastal structures. Also damages to coastal structures in different parts of the world occur with enough frequency to suggest that the state-of-the-art in the selection of proper design conditions for coastal structures, attached by irregular shoaling wave trains is not always good enough. Reference is made to BAIRD et.al. 1980 and to YAMAMOTO et.al. 1981.

Many engineers still belive that the use of long sequences of random waves for laboratory experiments offers a high probability that all extreme test conditions will be encountered sooner or later. Experience at NHL show that this is generally not the case. Most ordinary sea simulations in hydrodynamic laboratories with irregular waves in deep water conditions, does not show any appearances of plunging breakers. In a few cases large plunging breakers has been reported as a result of a random sea simulation, but when such waves suddenly appear by "chance", they are most often far away from the structure that is installed in the wave flume with the purpose to be tested, and then efficiency as well as time is lost.

Even more important is the fact, that responses such as surge and mooring force measured on a moored buoy at NHL was larger in very non-linear deterministic generated plunging breakers, than responses obtained in traditional testing with wave spectra. The same kind of experience have been made by MANSARD & FUNKE 1982, that reported that a capsizing occurred each time a large plunging breaker was striking on a buoy, but irregular waves for a fully developed sea failed to capsize the buoy. It is then documented that testing only in irregular waves can be directly misleading. Thus, the amount of high violent breaking waves that is contained in a sea, is a most important factor to consider for design of both offshore structures, ships and coastal structures. Some critical events might happen just in certain kinds of steep extreme waves, but the same events do not happen in a normal sea state described and simulated in the laboratory by the use of the traditional wave spectrum. Examples of the critical events we have to consider are given in Fig. 2. Such events could be dynamic snap loads or breaking of mooring lines, severe slamming loads or shock pressures giving local damage to steel plates as it is very commonly reported by ships. Other critical events could be the occurrence of an extreme roll connected with a possible shift of cargo, or the occurrence of an extreme acceleration. The wave energy supplied by a large plunging breaker on an ocean system such as a gravity platform must be transmitted to the foundations. The shock pressures that might occur on such structures, represents the larges and most severe dynamic loads a structure can be exposed to next to direct collisions with either icebergs or ships. These shock pressures appear with a high transient pressure peak that is superposed upon the normal cyclic wave load. The dynamic response of structures in terms of transient vibrations caused by shock pressures or slamming loads has therefore to be taken into account. Attempts in this direction has already been made.

CRITICAL EVENTS

- * Breaking Strength Exceeded
- * Plastic Deformation
- * Capsizing
- * Extreme Roll
- * Shift of Cargo
- * Shock Pressure, snap load, vibration
- * Damage to breakwater, sliding of blocks

Fig. 2. Examples of critical events.

Very often the designer has to investigate if a critical event might happen or not. If the answer is yes, the designer then has to decide if such an event is acceptable or not. Very often he will then raise the question: "What is the probability for such an event?" If the probability is very low, he might then find that the conditions are acceptable. However, if the probability is high, he will often find that the conditions are not acceptable and he will develop a new design. We are therefore now fased with a new design philosophy both for ships and ocean systems, and the new philosophy deals with the supreme basic problem to evaluate the seaworthiness of a ship or an ocean system either in a survival condition or in an operational condition. With an ocean system, we can here think of a semisub in transit, or a moored system such as an offshore loading system with a ship connected, or a fixed installation such as a guided tower, a jack-up or a gravity structure. All these ocean systems have that in common that they have to be installed and operate in a rough environment in deep waters.

The present paper deals with all aspects of this new design philosophy, as shown in Fig. 1, namely characterisation of extreme waves, selection of design sea states and design waves, an alternative new non-linear technology for the generation and simulation of selected rare extreme conditions in the laboratory using a deterministic approach, and finally the calculation of the probabilities for the freak wave events and critical respons events that might be observed from such experiments.

3. CHARACTERISATION OF EXTREME WAVES

It is not possible to characterize the severeness of a particular sea state containing large violent breaking waves in deep waters using a single wave parameter such as wave height. Experiences show that accidents at sea occur if there is a quite unique exceedance of critical threshold values for several parameters simultaneously. Wave steepness seems to be a parameter at least as important as wave height, under some special circumstances even more important. Traditionally wave steepness has been introduced as a ratio between total wave height and total wave length $s = H/L$ where the total height is a result of superposition of many individual wave components all of sinusoidal shape and with different dispersion directions in the sea. However, reliable measurements at sea of total wave lengths in space are very scarce, and in rough seas such measurements are completely lacking. All oceanographic measurements are traditionally performed with registrations from a single point at sea in the time domain.

A rough engineering evaluation of wave steepness has then traditionally been obtained from the ratio between the total wave height H and some wave period T. For instance T can be selected as a period obtained for single waves using zero-downcross analysis. We then obtain:

$$S = H/\frac{g}{2\pi}\cdot T^2 \qquad (3.0)$$

However, in general, finite amplitude storm waves at sea will not appear with a symmetric shape, but will have a pronounced asymmetry, both with respect to a vertical and a horizontal axis. This is due to a sheltering effect, which gives rise to pressure differentials ove the upwind and leeward side of the crests. Therefore in the synoptic space the parameter S = H/L does not define a steep asymmetric wave uniquely. A large number of asymmetric waves can exist, with the same total steepnees S, but with very different crest front steepnesses, see Fig. 3.

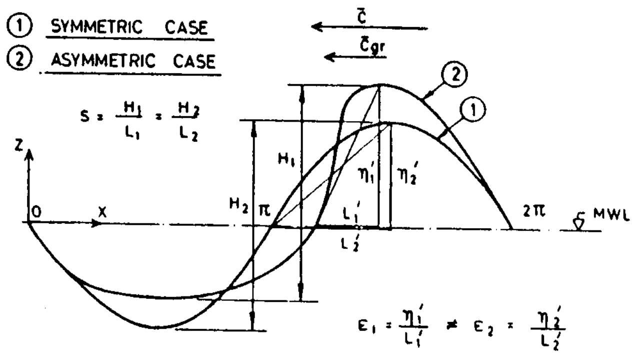


Fig. 3. The total wave steepness S = H/L does not define an asymmetric wave uniquely. (From KJELDSEN & MYRHAUG 1978).

A well defined quantitative description of transient highly asymmetric waves of finite amplitude approaching the point of breaking in a random sea is therefore needed.

The present study provides a more accurate description of steepness and asymmetry in transient near breaking waves, when a datum (MWL) and three new parameters are introduced.

- The datum MWL for analysis of field measurements made from floating devices such as ships and buoys is defined as the mean water level over a 20 minutes recording period.
- The datum MWL for analysis of field measurements made from fixed devices such as platforms or wave staffs is defined as a mean water level over a 20 minutes recording period with proper corrections for tide, if any.
- The datum MWL for analysis of laboratory experiments is defined as a still water level, as it can be obtained in a wave flume, before artificial surface fluctuations are generated.

The three new parameters that contain sufficient information for a unique quantitative description of deep water breaking waves, as they develop asymmetry and approach the point of breaking are the following:

Crest front steepness: $\varepsilon = \frac{\eta'}{L'}$ (3.1)

Vertical asymmetry factor: $\lambda = \frac{L''}{L'}$ (3.2)

Horizontal asymmetry factor: $\mu = \frac{\eta'}{H}$ (3.3)

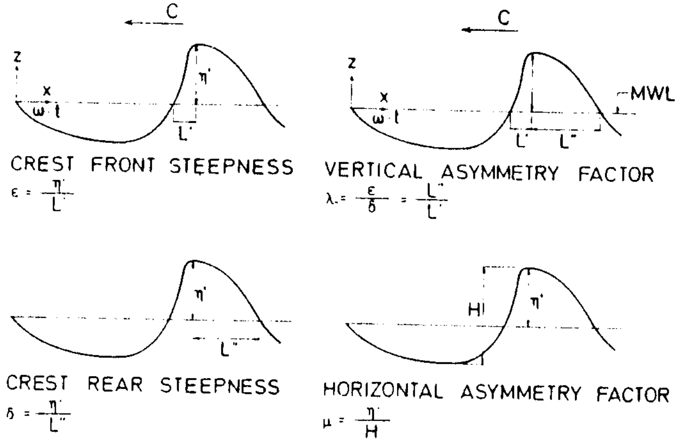


Fig. 4. Basic definitions for asymmetric non-linear waves that approach the point of breaking in a random sea. (From KJELDSEN & MYRHAUG 1979).

The definitions are shown in Fig. 4. Here, η' is the crest elevation measured from datum, while L' and L" are horizontal distances defining the position of the wave crest relative to the zero-crossing points. It is generally accepted that use of the crest elevation for design applications provides a basic parameter more relevant to finite amplitude wave geometry than the wave height. Observations of breaking waves show that these waves can be characterized by a very steep crest front and high asymmetry factors. The ε-parameter is thus a mean crest front inclination. Further, λ describes asymmetry with respect to the vertical axis in the crest, while μ describes asymmetry with respect to a horizontal axis in the mean water level. It is now possible to obtain a crest rear steepness directly as:

Crest rear steepness: $\delta = \frac{\eta'}{L''} = \frac{\varepsilon}{\lambda}$ (3.4)

A striking result of laboratory wave-focusing experiments performed in deep waters at NHL, is that the observed wave-wave interaction phenomena lead to the generation of breaking waves which can all be classified as (belonging to) three distinct types of wave shapes see Fig. 5. These wave shapes are completely different hydrodynamic modes, each with a different particle kinematics and a different energy dissipation.

The most remarkable is the deep water plunging breaker. It develops a strong jet in the front of the wave and has very high particle velocities and accelerations associated with that development. This breaker can be obtained either in deterministic focusing experiments where a large number of non-linear waves (solitons) suddenly are brought in phase with each other, or it might appear by chance in stochastic experiments with random waves. (Simulation of seas containing such waves will be further discussed in section 5).

The deep water bore is a double wave. It is a highly non-linear wave-wave interaction phenomenon. Two waves with different dispersion velocities interact. One of the wave phases overtakes the other wave phase. By doing so the upper wave starts to break on top of the lower one. Thus the breaking inception takes place in the rear part of the lower wave, and when a turbulent zone is generated it spreads, and finally we observe 2 waves on top of each other both breaking with a nearly vertical front. We still need an engineering description of such a storm wave. We name it a deep water bore because the visual appearance is quite similar to the more familiar tidal bore. Survivors from one of the accidents described above (research vessel "HELLAND HANSEN"), has given a description of such a single wave causing a capsizing: "It was a vertical wall of water breaking from top to bottom that approached us". The particle kinematics associated with such a breaker is unknown, and completely different from kinematics in other types of waves. Therefore also the duration of breaking as well as the energy dissipation are both much larger in a deep water bore, than in a normal "whitecap".

The spilling breaker is the most common. It contains air at the very top of the wave crest, the complete breaker is nearly symmetrical with respect to a vertical axis through the crest ($\lambda = 1$) and the angle of the crest is very close to 120 degrees. The particle kinematics is again different. The largest particle velocities are found at the top of the crest and are close to the phase velocity. That is not the case for the 2 other breaker types. Therefore in the spilling breaker the energy dissipation is small compared to the 2 other types of breaking waves. The spilling breaker is commonly known as a "whitecap".

Typical values for the parameters characterizing the different types of breaking waves obtained in wave focusing experiments at "the initiation of breaking" are:

$$\begin{aligned} 0.32 &< \epsilon < 0.78 \\ 0.26 &< \delta < 0.39 \\ 0.90 &< \lambda < 2.18 \\ 0.84 &< \mu < 0.95 \end{aligned} \qquad (3.5)$$

The same 3 types of breaking waves are observed in some experiments with prescribed wave spectra, where breaking waves appear in a random way. However, most experiments of this kind do not contain the plunging breakers, because an exact focusing of wave energy resulting in a phase-lock is missing.

Thus we conclude, that when we restrict ourselves to discuss breaking shapes, and modes of breaking in a 2-dimensional sea, we here have a classification of hydrodynamic breaking modes, and all observed breaking waves in a random sea might be classified as belonging to one of these 3 types. Fig. 5 shows examples of synoptic measurements of these 3 types of breaking waves obtained from a frame-to-frame analysis of a high-speed film recordings.

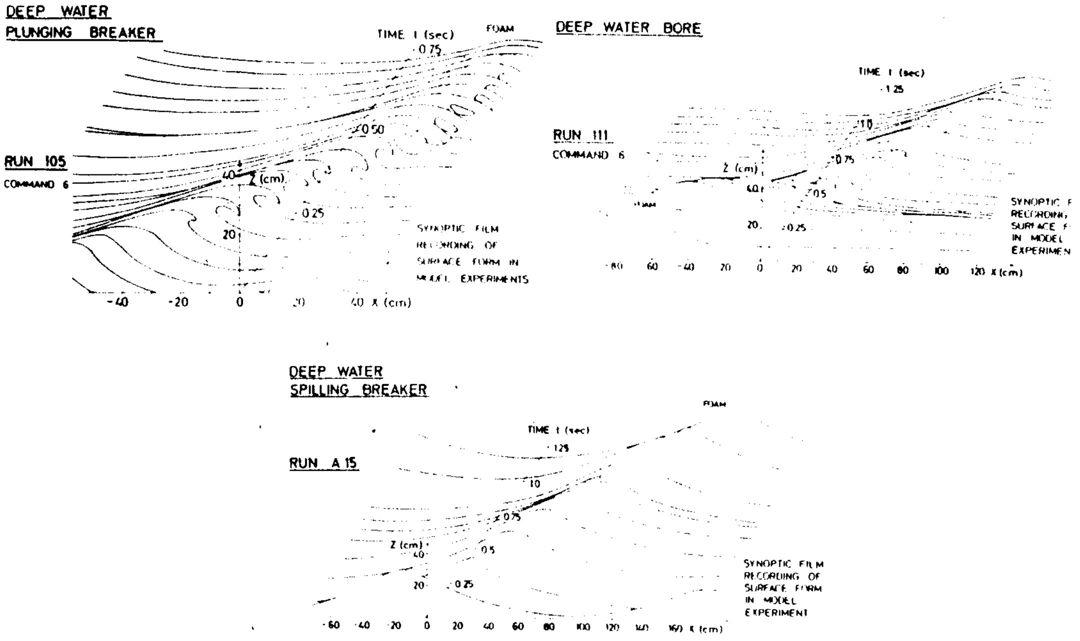


Fig.5 Classification of breaking waves in deep water. (From KJELDSEN & MYRHAUG 1979).

Many different shapes of breaking storm waves exist in deep waters during advanced sea states. However, it is obvious, than when we restrict ourselves to 2-dimensional longcrested breaking waves, the above classification is a valid engineering method for grouping of observations obtained both from random seas and deterministic seas. This is then the first step for an engineering treatment of interaction of different kinds of vessels or ocean systems with this kind of extreme waves. The second step is a detailed mapping of wave kinematics, associated with these 3 types of waves, and the third step is a prediction of loads and movements.

Freak waves are known to occur in particular where opposing ocean currents are present. Therefore examples of tracking and mapping of large breaking waves in synoptic space, in laboratory experiments with opposing currents are most illustrative. The particular amplification of gravity waves from the combined effects of a deterministic phase relationship (using command signals to wave generators as described in section 5) and an opposing ocean current was investigated experimentally at NHL. Fig. 6 shows results from such experiments plotted as synoptic measurements of the crest front steepness as it was obtained using a special high-speed film-technique with a rate of 500 frames/second followed by a frame to frame analysis. 2 conditions are shown in the plot. The first condition refers to a freak wave with a deterministic phase relationship resulting in wave focusing and all individual wave components in phase with each other. The second condition refers to the same freak wave, but now a steady opposing current is present in the wave flume, where the freak wave is generated. In both cases the freak waves breaks as plunging breakers in deep water, but in the second case the breaker is much more violent, the jet is much stronger and therefore the duration of breaking is much longer as it can be clearly seen in the Figure. (The duration of breaking is here defined as the time from the wave has a vertical front untill the time where the jet strikes into the water level(ahead of the wave). In the diagram the zero-downcross period T_B for the breaking wave is used for normalisation. Also the velocity of the mean ocean current V is normalised with respect to a nominal linear phase velocity calculated for the freak wave as $C_{OB} = \frac{g}{2\pi} \cdot T_B$ where g is the acceleration of gravity. In other words this means that the velocity of the current in this particular experiment was 2% of the phase velocity for the interacting freak wave involved. If the wave thus has a period of 12 seconds corresponding to a phase velocity 18.7 m/sec (or 37 knots), the mean current velocity in the experiment then corresponds to 0.37 m/sec (or 0.7 knots), which actually is a quite moderate current velocity, that is exceeded in many ocean currents where velocities in the range 1 - 2 knots are quite common, and under certain circumstances where eddies are formed by coastal currents even higher velocities occur.

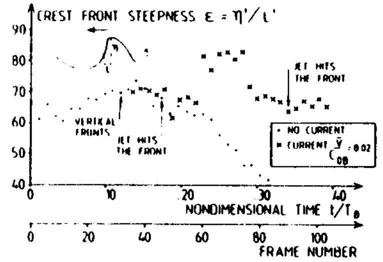


Fig. 6. Amplifaction of crest front steepness by an opposing shear current. (From KJELDSEN & MYRHAUG 1980).

Fig. 7 shows a similar diagram. Here the change of the horizontal asymmetry factor for a focused freak wave without and with an opposing current is plotted. When no current is present the ratio between the wave crest and the total wave hight in front of the wave, measured with respect to the mean water level was 0.81. (the mean water level in this experiment is defined as the still water level in the wave flume before start of mechanical wave generation). For the case where an opposing current was present, the wave continued to steepen up even after it had reached a vertical front, and the maximum ratio between the crest height and the wave height measured in front of the wave became 0.87 a value that was reached just before the jet was striking in the water level ahead of the wave. Further details with photos from the high-speed film recordings are given by KJELDSEN & MYRHAUG 1980.

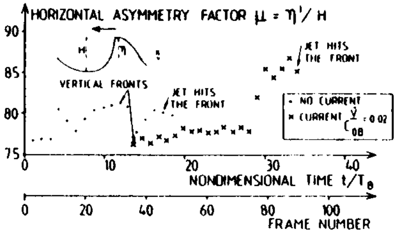


Fig. 7. Amplication of horizontal asymmetry factor by an opposing shear current. (From KJELDSEN & MYRHAUG 1980).

Now nearly all oceanographic measurements obtained at sea are recordings of waves in the time domain obtained at a single point. With the purpose to obtain information about wave asymmetry and a possible non-gaussian behaviour of storm waves, we can redefine the asymmetry parameters for the time domain in th following way, see Fig. 8:

Crest front steepness: $$\varepsilon = \frac{\eta'}{\frac{g}{2\pi} T \cdot T'} \quad (3.6)$$

Vertical asymmetry factor: $$\lambda = \frac{T''}{T'} \quad (3.7)$$

Horizontal asymmetry factor: $$\mu = \frac{\eta'}{H} \quad (3.8)$$

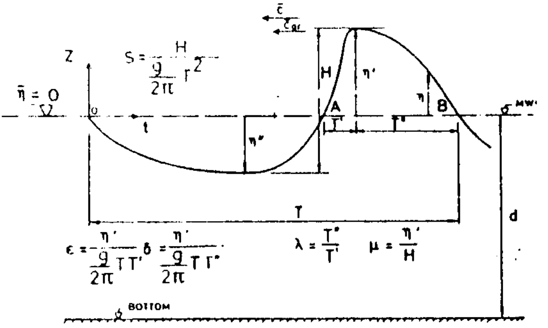


Fig. 8. Definition of wave parameters in the time domain. (From KJELDSEN & MYRHAUG 1978).

A complete conversion from time to space requires exact knowledge of the total directional spectrum for the particular sea under investigation. However, using the zero-downcross wave period in the manner described here provides us with a simple engineering half-cycle counting technique in the time domain, that then can be applied for studies of responses from single extreme waves such as slamming, extreme roll, extreme acceleration or capsizing.

The present study utilizes the advantages that are contained in a zero-downcross analysis. This analysis uses the wave trough and the proceeding wave crest in the definition of a single wave, and defines the wave height as the difference between these water levels, Fig. 9. (The conventional zero-upcross analysis used by most oceanographers defines a single wave as a wave crest and the following wave trough, and thus obtains a wave height behind and not ahead of a possible breaking wave.) The zero-downcross analysis is therefore believed to be the only analysis which provides parameters that are a representation of the physical conditions relevant to breaking waves, and thus the zero-downcross analysis is the only analysis that provides wave parameters which should be used by naval architechts and engineers for correlation with measurements of ship response or wave slamming.

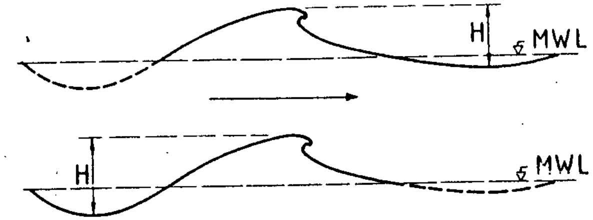


Fig. 9. Synoptic experimental recordings of development of breaking waves, showing the basic difference in definitions of single waves in zero-downcross and zero-upcross analysis.(From KJELDSEN, LYSTAD and MYRHAUG 1981).

4. CHOISE OF EXTREME WAVETRAINS FOR DESIGN AND TESTING

In the following we shall now treat the important question: "Is there any way to plan a series of either model experiments and/or numerical simulations of responses of ocean systems, which can represent the most critical sea condition during the life of this structure, in such a way that design values for motions and wave loads can be obtained directly?" To answer this question the following 2 problems must be treated:

1) What is the design sea state?

2) What is the most critical sequencies of wave trains in an irregular sea, evaluated in the space and time domains?

Evaluations of design sea states both for the survival condition and for the operational condition for an ocean system is usually determined from the long-term statistics available from the area for installation or operation, see HAVER 1983. In the many cases where wave measurements only are available for very few year, statistical methods for long-term predictions of wave climate fail. In such cases improvements of long-term wave statistics can be obtained using hindcasting techniques, see KJELDSEN, LYSTAD, MYRHAUG 1981. After the performance of such an evaluation, a design sea state, where significant wave height and the modal wave period are specified, both for survival and for operational conditions can be obtained. Next the shape of the spectrum must be assessed. This is a quite uncertain procedure. If a heavy swell and a wind sea is superposed with different main dispersion directions, the spectrum in the specified condition might have two significant peaks. However, the usual standard is to disregard the presence of a swell, and to specify the wave spectrum for the design sea state either as a Pierson-Moskowitz, a JONSWAP- a ISSC-, or a ITTC-spectrum. However, we are now faced with the severe problem, that the selected wave spectrum by no means is sufficient to characterize the design sea states. Recent extensive analysis in the time domain of series of irregular waves with completely identical wave spectra, reveal that some of the time series contain extreme single freak waves with very high values of the parameters ε , λ and μ while others not contains such waves see KJELDSEN & MYRHAUG 1979. Therefore a specification of a random sea by the wave spectrum alone is insufficient. Also from an analysis performed in Canada the same kind of conclusions regarding insuffiency of the wave spectrum has been derived see JOHNSON, PLOEG, MANSARD 1978. So we are now faced with the second and much more severe problem, to assess by engineering methods the most critical sequences of wave trains an ocean system might encounter in the lifetime of the structure.

A solution to this second problem is also available. As every sailor know it is the crest front steepness of the high waves that is most important to consider, and not the wave height alone. The most lately research, performed in the project "SHIPS IN ROUGH SEAS" concludes that severe accidents at sea resulting in capsizings of smaller vessels, occurred when exceedances of thresholds limits in the two governing parameters crest front steepness and wave height took place simultaneously. Reports show that it was not the very high waves, but waves with a medium height (> 5 m), and a very pronounced crest front steepness that actually capsized the vessels (see VÅRHEIM & NEDRELID 1980).

A very rough sea state can therefore only be satisfactorily described as an event that contains both high values for the wave heights and high values for crest front steepness and asymmetry parameters. High values of crest front steepnesses combined with low values of wave heights describe a choppy sea, but this is not disastrous. Low values of crest front steepnesses combined with high values of wave heights describe a heavy swell. It is therefore the joint probability density distributions for high values of both crest front steepnesses and wave heights that describe a very rough sea, and not the percentage of breaking waves itself. Thus, severe breaking waves is a term that refers to a condition with high values of both wave height and crest front steepness. It is therefore only the joint probability density distribution for these two parameters that provides the naval architecht with sufficient information for a risk analysis. Measurements of such a joint probability distribution are performed on the Norwegian Continental Shelf and is presented in section 7 together with probability evaluations for freak waves. Fig.10 illustrates this new concept. A scatter diagramme for the single waves in a particular sea state is plotted with one axis for the crest front streepness, and one axis for the zero-downcross wave height. Further if we define some critical threshold values both for the wave height H_{crit} and for the crest front steepness ε_{crit} we are able to classify all waves into four categories, namely:

1) Small waves
2) Heavy swell or high waves with moderate steepnesses
3) Choppy sea
4) Severe breaking waves

As the crest front steepness increases also the physics involved when a large deep water wave steepens up and actually breaks, becomes very important here. This is illustrated in Fig.10 where the area in the upper right corner is the main one, that should be considered, when a possible risk for an extreme response is evaluated. The actual size of this area and the definition of critical threshold values H_{crit} and ε_{crit} should be determined from laboratory experiments, and might thus vary from one problem to another dependent of the charateristics of the floating structures involved.

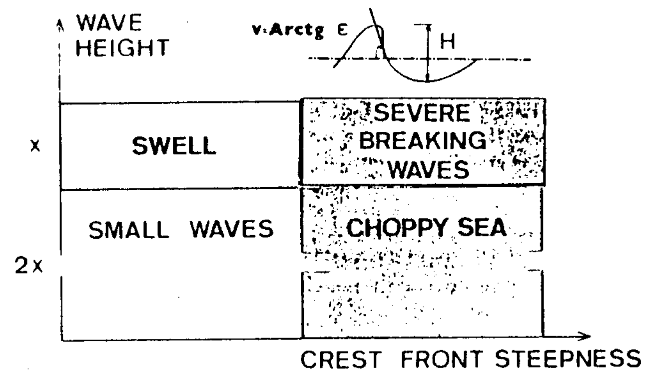


Fig. 10. Classification of individual waves in a sea state with use of a joint probability density distribution of individual wave heights and crest front steepnesses. (From KJELDSEN 1981).

This implies that marginal probability density distributions (such as the Rayleigh distribution for wave heights alone) not is sufficient for a risk assesment. This implies further that a very rough sea state must be evaluated in the time domain, and not can be described in a satisfying way for the engineer using only the wave spectrum in the frequency domain.

We are now able to select and specify particular dangerous wave situations for survival tests. Such tests should be designed to generate irregular deterministic wave trains that contains waves with a high joint probability for exceedance of both the critical threshold limit for the crest front steepness and the critical threshold limit for the wave height at the same time. Now a physical realisation of such a condition implies that we simulate in the laboratory in a deterministic way, a wave train that focus exactly on the ocean system to be tested and contains the build-in development of large single freak wave, that suddenly appears as a large physical transient out of proportions to all other waves in the simulated sea state, and breaking violent as a plunging of breaker in deep water. This is then a true freak wave.

A design procedure is now developed at NHL for command signals to wave generators that makes it possible to design wave trains that contains such freak waves, in such a way that the appearing freak wave matches with dimensions in terms of height, crest front steepness, period and direction with the individual ocean system that has to be tested. The design of command signals starts with the design sea state for the area where the ocean system has to be installed or operate. From the design sea state freak waves with a reasonable probability can be extracted. Such freak waves must then be designed to match critical periods for roll or resonance in the ocean system and they might either occur as single waves with specified frequencies, or as the last wave in a wave train with a frequency that matches the critical roll period or an envelope that matches other critical periods in the system. The following discussion will now be divided into two parts. In the first part we will discuss the situations that has to be simulated for a small vessel. In the research project "SHIPS IN ROUGH SEAS" not less than 7 situations are identified as important, see Fig. 11.

These are

1) General roll conditions in a moderate beam sea.

2) Striking of a single freak wave breaking as a plunging breaker in deep water. Extreme roll motion and shipping of green water in a beam sea.

3) Build-up roll motions in a regular wave train that matches the natural period of roll for the vessel and is followed by a direct strike of a deep water plunging breaker that also matches the natural period of roll.

4) In the following sea the well known phenomenon of loss of stability on a wave crest, travelling with a phase velocity equal to that of the ship.

5) Parametric coupling i.e. increasing roll amplitudes in a near regular following sea or in a head sea.

6) Broaching in large breaking waves. (The vessels most often reports on broaching events in deep water breaking waves of the spilling type. These are waves for which the duration of breaking can last for several wave periods).

7) A 3-dimensional quartering sea containing combinations of beam seas and stern seas, and attack of plunging breakers on the stern with shipping of green water as a result.

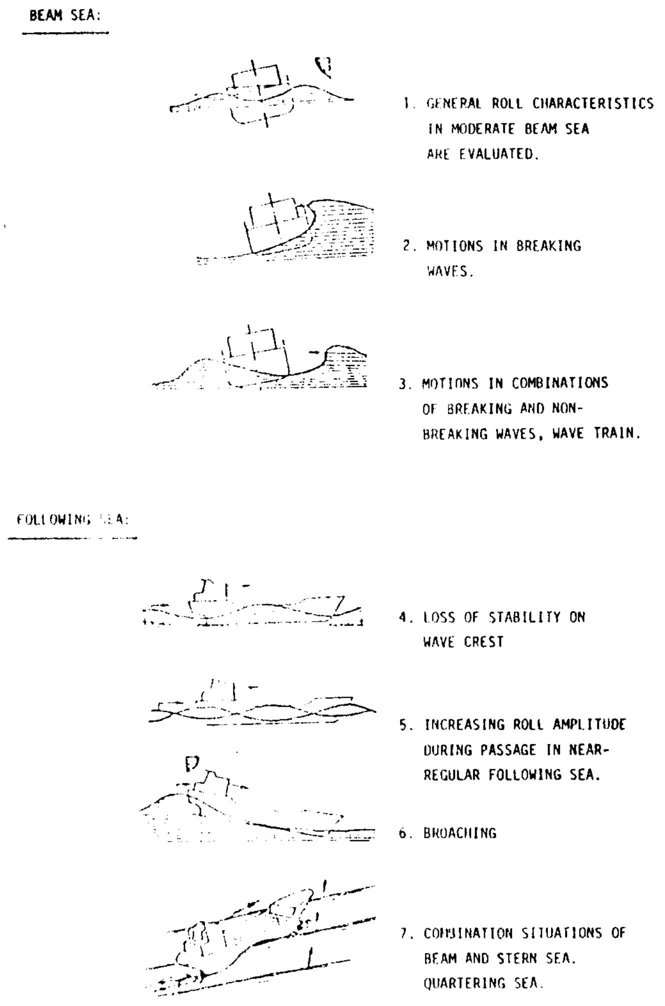


Fig.11. Identification of important situations for a small vessel operating in severe seas (From NEDRELID see NSFI/RINA publication 1982)

One condition that not is shown in Fig. 11, is the event of capsizing (bow over stern) in head seas. Evidences of such events exist for smaller vessels. One example is the famous photograph presented by ADLARD COLES 1980 p 260, but other cases are reported. The phenomenon is well known when small boats are launched from a shallow beach into a heavy surf. Therefore historically the multihull vessel was developed in the Pacific region in order to increase stability in surf.

We shall now turn to the second part of the discussion and consider ocean systems such as moored buoy systems, semi-submersibles moored or in transit, offshore towers hinged at the sea bottom, steel jacket structures and gravity platforms. 6 important situations to consider are shown in Fig.12. These are:

1) Focusing of all wave components in a wave collision which appear exactly at the ocean system as a large plunging breaker followed by a large hump. A freak can also appear as a very large hump in the sea surface, and this can be just as severe as a very large crest. (Assuming a δ-function at the position of wave concentration, and measuring the response from a concentrated wave give a direct experimental determination of the transfer function for the ocean system involved, see KJELDSEN 1982.)

2) Wave trains matching critical natural periods of oscillation (or superharmonics of natural periods of oscillation) followed by a plunging breaker also matching the critical period of oscillation (or superharmonics). If natural periods of the ocean system under consideration are very long, envelopes of wave trains should match the natural periods or superharmonics of natural periods.

3) It is most evident that the motion of an ocean system during the ultimate wave cycle immidiately before the attack of the plunging breaker is most important for a possible critical event and for motion safety. (A capsizing accident for a smal vessel in beam seas was found to depend on the motion of the vessel towards the plunging breaker or away from the plunging breaker). Therefore testing in a random stochastic sea that contains a focusing of all wave components at certain intervals as large plunging breakers (repeating freak waves) is one of the best alternatives available for experimental testing of an ocean system. The one-diminsional spectrum for the random sea can be designed to fit either the Pierson-Moskowitz, the ITTC-, the ISSC- or the JONSWAP- Spectrum.

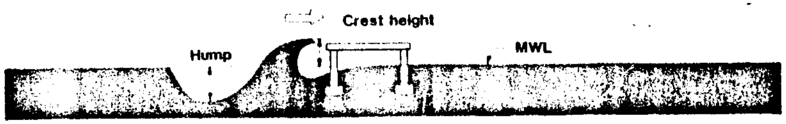
4) 3-dimensional focusing of wave energy in a random sea with a prescribed directional spectrum. A 3-dimensional focusing of wave trains on an ocean system will result in freak waves with larger crest heights than the 2-dimensional focusing. Plunging breakers can now attack from several directions simultaneously in antiphase with each other. The wave crest lengths are now an important factor for the responses such 3-dimensional breaking waves give rise to. In nature such focusing exist on the leeward side of shallow shoals or in zones with strong ocean currents opposing the main dispersion direction of the waves. An example of an accident in such an area will be treated in section 6. If possible passages of such areas by small vessels should be avoided during severe gales.

5) Situation 1) - 4) with the following superposed:
a) A current from an arbitrary direction.
b) A swell from an arbitrary direction.
c) A wind gust, and a mean wind velocity.

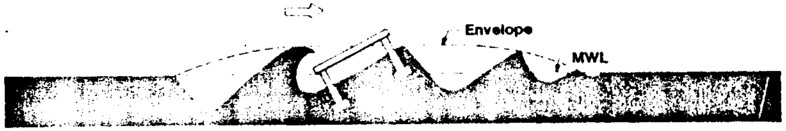
In Norway several large research projects are in work studying the probabilities for simultanous extreme values of waves, wind and current. For tests with a vessel where a capsizing might occur, the effects of wind velocity and wind gusts can not be neglected.

6) Effects of topography in shallow waters such as refraction behind shoals, and further refraction of waves by ocean currents in deep or shallow waters.

① **Attack by single freak wave:**
Mapping of transfer function :

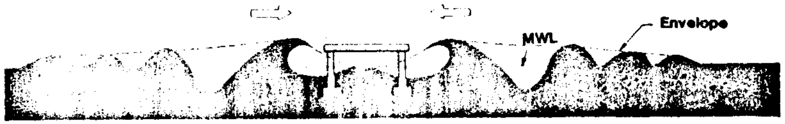


② **Attack by wave train with envelope matching critical natural periods of oscillation followed by a large plunging breaker and a large hump also matching the critical period of oscillation or alternatively matching superharmonics to the critical period of oscillation :**



③ **2-dimensional focusing of freak wave in a random sea with prescribed one-dimensional spectrum (Pierson- Moskowitz, I.T.T.C. , I.S.S.C. or Jonswap) :**

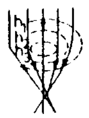
④ **3-dimensional focusing of freak wave in a random sea with prescribed directional wave spectrum :**



⑤ **Situation (1)-(4) with the following superposed:**

(a) Current from an arbitrary direction
(b) Swell ———— " ————
(c) Wind gust and mean wind velocity

⑥ **Effects of topography in shallow waters such as refraction behind shoal:**



Refraction of waves by ocean currents in deep or shallow waters

Fig. 12. Identification of important situations for an ocean system, operating in severe seas.

For the moored offshore structures it has long been observed that motions and mooring loads vary with the envelopes of the waves in a random sea. The horizontal oscillations such as surge, sway and yaw for large vessels have natural periods in the range 20 - 200 seconds far greater than wind generated seas. In a moored condition the largest responses of such vessels would be expected when the periods of the wave groups matches these natural frequencies, see MANSARD & PRATTE 1982.

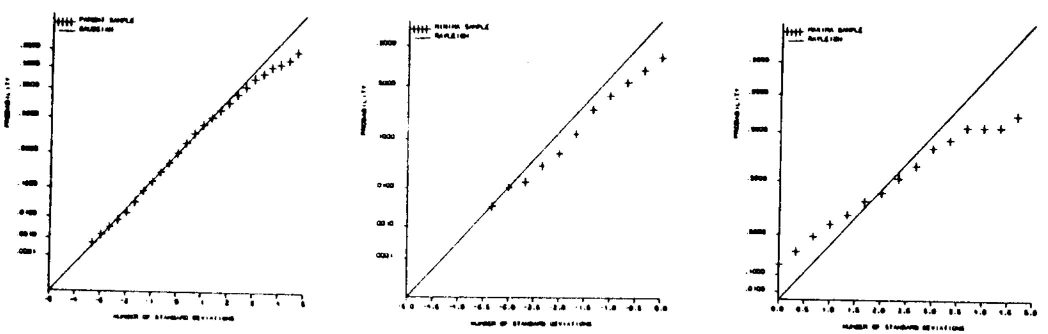
Such a matching can be obtained by random simulations, but much more efficiently by a direct design of a command signal that contains deterministic wave trains with prescribed envelopes. For a satisfying modelling of such slow-drift phenomena it is well known that the frequency spacing must be small, compare NÆSS 1978. LONGUET-HIGGINGS & STEWART 1964, has shown that a set-down of mean water level occurs below wave groups with a corresponding set-up between the wave groups. However also the mechanical wave generators can give rise to long waves, occurring as a parasitic noise, not present in the natural wave spectrum that has to be simulated. Such parasitic long waves are most dominant in shallow waters and should be avoided in experiments designed to measure slow-drift phenomena.

SPIDSØE et al 1983 analysed fullscale measurements of dynamic responses of 3 gravity platforms on the Norwegian Continental Shelf. The dynamic responses of the platforms was expected to appear in the frequency range for the wave energy and at the natural frequencies for the platform. In november 1981 a severe storm passed the FRIGG field, wind velocities were 70 knots, and significant wave heights were 14 m. Under these conditions SPIDSØE et al. found a significant departure from the Gaussian condition both for the measured waves and for the measured responses in terms of acceleration at the top of the caisson and in terms of bending moment at the bottom of the shafts, on the platform TCP-2, see Fig.13. SPIDSØE et al. 1983 concludes: "Non-linear waves which causes non-gaussian responses has been observed, and the loads caused by these waves are significantly higher than linear waves would give. This is an effect which is not accounted for in the theoretical model normally used for simulation of dynamic response of gravity platforms."

Thus it will be the scope of a well planned and well designed experiment in a hydrodynamic laboratory to measure extreme loads and extreme responses of this kind due to the passing of non-linear wave trains. With such a scope, use of the traditional irregular random sea based on linear assumptions can be abandoned.

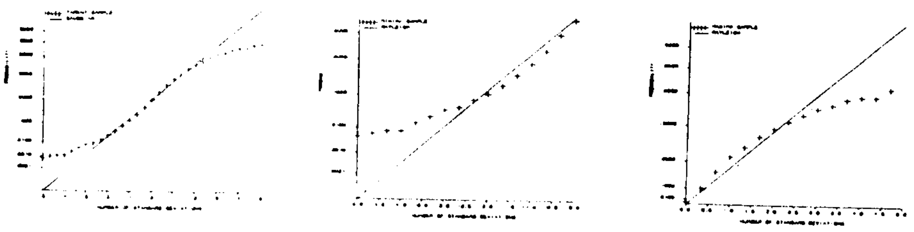
FRIGG - 811124 at 15h00

Sample probability distributions for wave heights



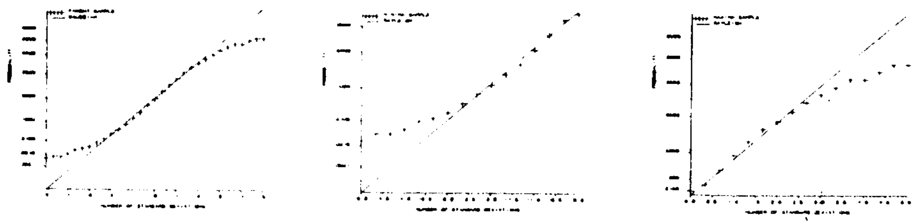
(a) Parent distribution (b) Minima distribution (c) Maxima distribution

Sample probability distributions for linear acceleration at top of caisson of FRIGG TCP2



(c) Resonant response

Sample probability distributions for bending moment, bottom of shaft of FRIGG TCP2



(c) Resonant response

Fig. 13. Non-gaussian waves giving rise to non-linear responses measured at the platform TCP-2 at the FRIGG-field west of Norway. (From SPIDSØE & HILMARSEN 1983)

5. GENERATION OF WAVE TRAINS CONTAINING EXTREME WAVES

In the following a brief summary of available wave generation techniques shall be given. Perfection of generation techniques for steady state longcrested, regular gravity waves (Stokes waves, cniodal waves and sinusoidal waves) may be regarded as a first step in state-of-the-art of wave generation in hydrodynamic laboratories. The most interesting here is the non-linear generation techniques for Stokes waves in deep waters and cnoidal waves in shallow waters. However, it is also very well known that a sinusoidal command signal applied to a wave generator will not lead to generation of a sinusoidal wave train. Instead irregular waves are observed in the wave flume with the basic frequency superposed with freely travelling higher harmonics. Thus, the simple demand to reproduce a "clean" simusoidal wave train in a wave flume without parasitic disturbances demands a laborous phase-compensating technique, in which higher harmonics is supplied artificially in antiphase with the unwanted parasitic noise. This technique is well known and described by BUHR HANSEN, SCHIOLTEN & SVENDSEN 1975. The present paper will deal with the more complicated non-linear generation technique for generation of Stokes waves in deep waters. The second step in state-of-the-art of wave generation techniques in laboratories is then the generation of a steady state stochastic sea containing irregular wave fields in 2- or 3-dimensions. The available techniques for generation of stochastic seas are all linear and are based on the use of Fourier analysis and one-dimensional or directional wave spectra.

However, both the directional spectra for the 3-dimensional wave field, and the common frequency spectra for the 2-dimensional longcrested wave field must necessarily be truncated, due to the physical limitations in the frequency range that is present when a prescribed spectrum is simulated artificially with mechanical wave generators. In simulations of a directional spectrum the selection of the truncation parameter affects the magnitude of the spectral moments m_0, m_2 and m_4, and also the obtained crest lengths that are achieved in the experiment (KJELDSEN & PRICE 1982). Further, it is well documented that the frequency spacing in the spectral simulation is essential for correct reproduction of slow-drift phenomena. However, even the two-dimensional directional sea spectrum appears to be insufficient, for a proper description of sea states containing extreme waves, and wave trains with sequences of breaking waves arranged in groups. Several radically different time series have been found -some containing violent breaking freak waves or wave groups - others not, and all have the same wave spectrum (JOHNSON, PLOEG, MANSARD 1978).

A theoretical storm model based on non-linear theory for collision of wave solitons, are presented by KJELDSEN 1982. This model can be directly used to prepare analog signals for wave generators. Since 1977 experiments of this kind have been performed at the Norwegian Hydrodynamic Laboratories in 3 different wave flumes, first one 33m long, 1m wide and 1.6m deep, second one 78m long, 4m wide and 1.6m deep, and the third one 280m long, 10m wide and 10m deep, all equipped with flap-type wave generators. Fig. 14 gives an example of such an experiment performed in the third wave flume. A deterministic collision between 43 transient wave components was arranged, and this resulted in a large freak wave breaking as a plunging breaker at a predetermined time and location in the wave flume. In the experiment shown in Fig. 14 the plunging breaker had a wave hight 0.74m and appeared 66 seconds after the start of the transient signal at a distance 41m from the wave generator. As it can be seen, the use of deterministic technique results in a very exact focusing in one single freak wave at a time and at a position in the wave flume that can be predetermided. Also the type of breaking after the classification given in Fig.5 can be preselected. Further this kind of deterministic experiment can be designed in such a way that a particular wave spectrum such as the JONSVAP-spectrum is matched accurately by the individual transient wave components, leading to the freak wave, and the envelope of the deterministic wave train can be matched to certain natural frequencies, in order to investigate slow drift in moored configurations.

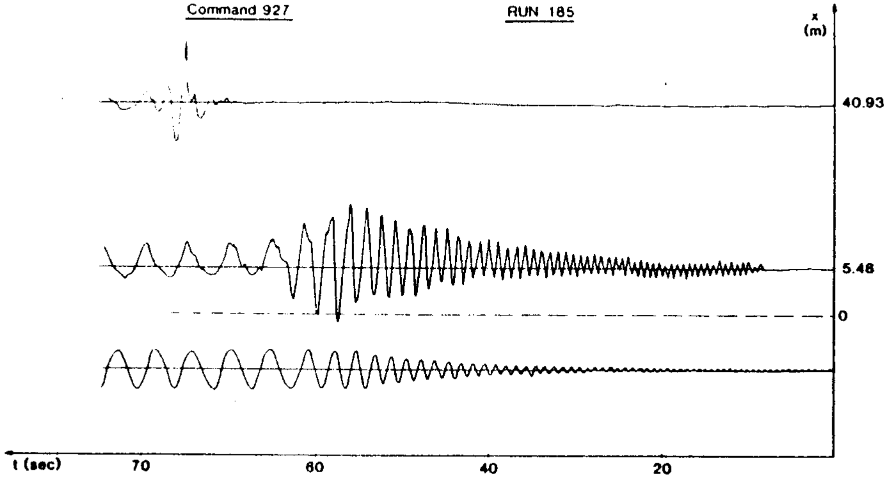


Fig. 14 Deep water plunging breaker generated from an interaction of 43 single wave components. The command signal to the wave generator is shown at the bottom. (From KJELDSEN 1982).

Fig.15 shows results from 11 repeated experiments of this kind. Measured parameters are trough-to-crest wave height H_{zd}, zero-downcross wave period T_{zd}, horizontal asymmetry factor μ defined as the ratio between creast height and wave height, and finally crest front steepness ε_t. For each parameter both the mean value and the standard deviation σ are shown. From this result compared to 16 mm high speed film recordings of the plunging breaker, we conclude that the repetition in the generated freak waves is excellent.

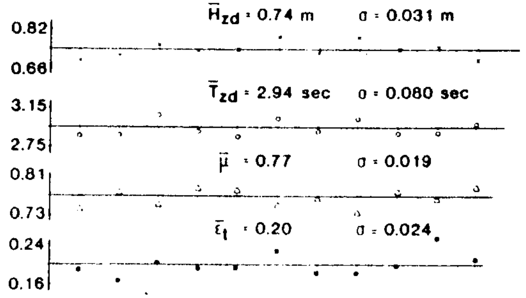


Fig. 15. Control of repetition in freak wave experiments. (From KJELDSEN 1982)

Finnaly, Fig. 16 shows a comparison between 3 identical transient tests with the same analog command signal but with a different gain on the wave maker. The positions x_B where the wave fronts become vertical are recorded and measured on high speed film and shown on the figure. Thus, when the gain is changed from 800 to 1000 the plunging breaker is shifted downwards in the wave flume from $x_B = 40$ to $x_B = 44.3$ m. This is a true non-linear behaviour. Dispersion velocities of all wave components increase with increasing amplitude, and the experimental technique and control are advanced enough to keep the wave focusing properties. Thus, this new non-linear experimental technique can be used to finally adjust a violent plunging breaker to give a very direct strike on a test structure placed for instance 42 m from the point of wave generation. Thus, this particular experiments is most suited for special investigations of dynamic effects from the waves on ocean systems such as slamming, occurrences of shock pressures or snap loads. Such measurements are dependent on generation of plunging breakers in deep waters that has a very direct strike on the installed model measured in the cm-scale. A few centimeters deviation in the direction of wave dispersion in such tests will give different results. The non-linear command signals to the wave generators admit a transfer of the plunging breaker position in the cm-scale simply by adjusting the gain slightly, while phase-lock conditions are maintained. The developed command signals has a total capability of transferring plunging breakers 4.5 m forwards or backwards in the wave flume as shown in Fig. 16.

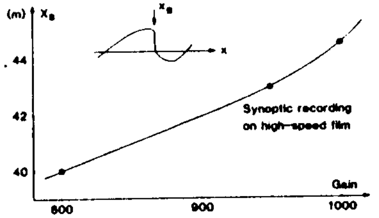


Fig. 16. Non-linear transfer of breaking point as a result of increase in gain on analog signal to wave generator. (From KJELDSEN 1982)

The work mentioned above is not restricted to long crested freak waves. The development of a 3-dimensional deterministic storm model has therefore been undertaken with the purpose to generate freak waves with a finite crest length under controlled conditions in the laboratory. The influence of crest length compared to main dimensions on a structure during testing is clearly most important both for evaluation of the overall extreme response, and for the event of a capsizing.

Experiments with a 3-dimensional focusing of many wave trains arising from different directions and resulting in one single short-crested breaking freak wave were performed in the new ocean simulation basin at the Norwegian Hydrodynamic Laboratories at the Ship and Ocean Division.

The princip is shown in Fig. 17. The ocean basin has a length of 80m, a width of 50m and a depth 10m. At the 80m long side an electrically driven hinged single-flap type generator with 144 individually controlled flaps is installed. At the 50m long side a hydraulic driven hinged double-flap type wave generator is installed. Here the double flap is 50m in width and extends 2.6m below mean water level. At the other two sides are efficient energy absorbing parabolic beaches. With this arrangement deterministic wave trains from many directions have been concentrated simultaneously in a single point creating violent deterministic 3-dimensional pyramidal breaking seas. It shall be emphased, that each of the deterministic wave trains used here alone will create a longcrested freak wave. The present experiment thus represents a superposition of freak waves from many directions simultaneously. Then later these kind of deterministic transient experiments have been superposed on steady stochastic wave fields, with specified directional spectra. Fig. 18 shows an example of such a short-crested freak wave.

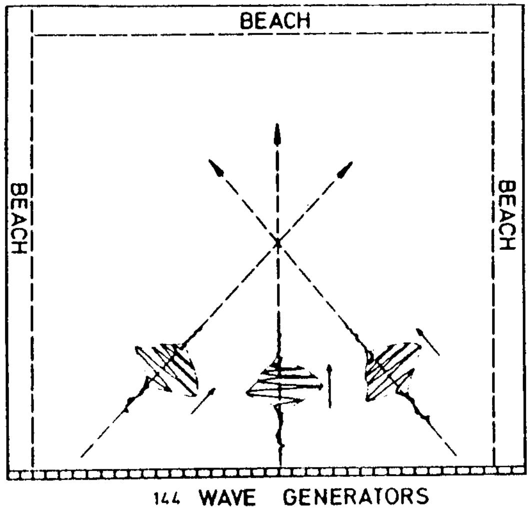


Fig. 17. Generation of 3-dimensional short-crested freak waves in the new large ocean simulating basin at NHL.

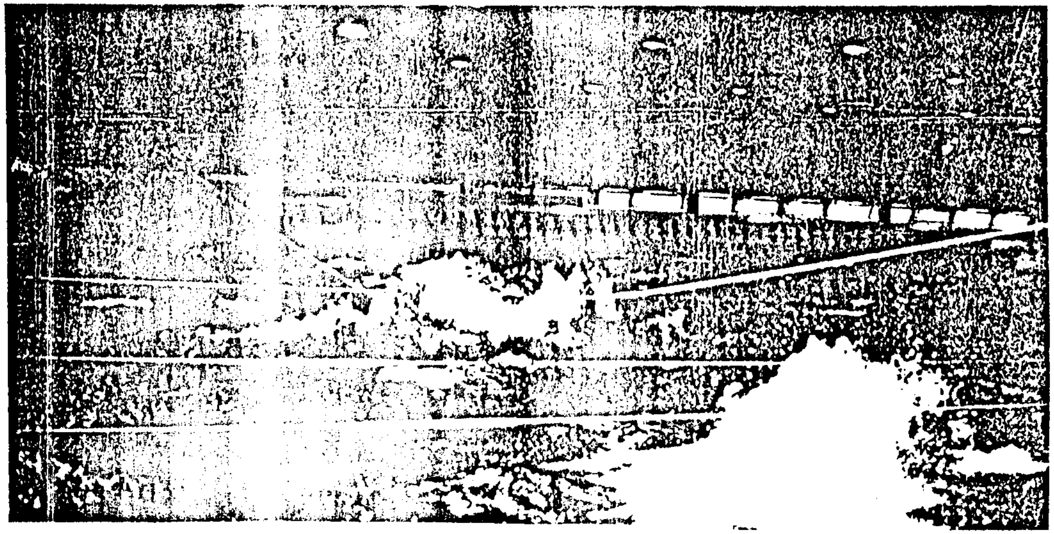


Fig. 18. Example of 3-dimensional short-crested freak wave in the new large ocean simulating basin at NHL.

Fig. 19 gives a summary of all available combinations of wave generation techniques. NHL is particular active on item No. 3, 4, 8, 10 and 12.

Art of wave generation · steady state

1	Regular Sinusoidal Waves	Linear	Deep and shallow water
2	One-dimensional Spectrum	—	—
③	Directional Spectrum	—	—
④	Stokes Waves	Non-linear	Deep water
5	Cnoidal Waves	—	Shallow water

Art of wave generation · transient state

6	2-Dimensional Freak Wave	Linear	Shallow water
7	2-Dimensional Freak Wave	—	Deep water
⑧	2-Dimensional Freak Wave	Non-linear	—
9	3-Dimensional Freak Wave	Linear	—
⑩	3-Dimensional Freak Wave	Non-linear	—

·Combined steady state/transient state

11	One-dimensional Spectrum with superposed Freak Wave	Linear	Deep Water
⑫	Directional Spectrum with superposed Freak Wave	—	—

Fig. 19. State-of-the-art in wave generation techniques.

The large new ocean simulation basin at Norwegian Hydrodynamic Laboratories has facilities for simulation of currents from an arbitrary direction, and simulation of wind and wind gust in addition to the wave generation techniques. For maneouvering tests in 3-dimensional irregular seas either with vessels or with ocean systems in transit it is the encounter wave frequency that should be considered. Thus it is no longer only the generated wave frequency that should be considered but the velocity and the heading of the vessel has to be taken into account when an experiment is planned. In a dimensionless term the encounter frequency is given as:

$$\delta_e = \omega_e \sqrt{\frac{L}{g}} = \delta(1 - F \cdot \delta\cos\chi) \qquad (5.1)$$

where ω_e is the cyclic frequency of encounter, L is the total length of the ship,

g is the gravity acceleration, $\delta = \omega\sqrt{\frac{L}{g}}$ is the dimensionless cyclic wave frequency,

$F = \frac{U}{\sqrt{Lg}}$ is the Froude number, U is the forward velocity of the ship, and χ is the heading.

As shown by ST. DENIS & PIERSON 1953 in head seas, for one set of dimensionless quantities δ_e, δ, F, χ there exists only one absolute wave frequency or wavelength condition that might lead to resonance with a given natural oscillation. On the other hand, in following seas three conditions may exist as shown in Fig. 20. Thus if any ship motion is found to be severe at an encounter frequency δ_e then it is clear that there may exist three times more possibilities of exciting this severe motion in following seas than in head seas. Hence, following waves can pose a much greater threat to the safety of the ship than head waves, as is illustrated in Fig. 20.

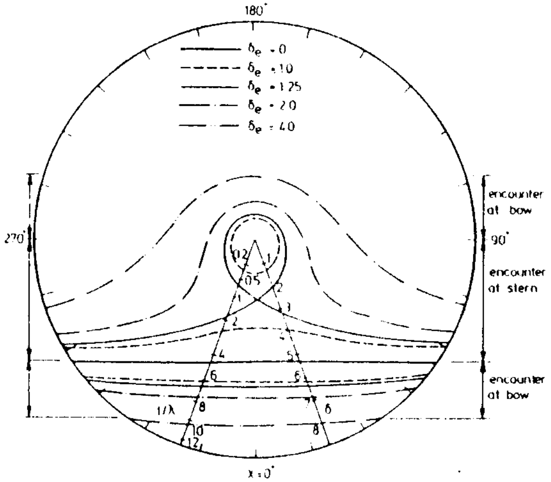


Fig. 20. Polar curves of dimensionless wave frequency δ_e and heading angle χ for F = 0.2. When δ_e < 1.25 the curves consist of one closed and two open branches; when δ_e > 1.25 the curves consist of two open branches. (From KJELDSEN & PRICE 1982).

Thus command signals for transient freak waves that shall match natural frequencies of rolling on moving models shall be constructed from the diagram shown in Fig. 20 and priority shall be given to following sea conditions.

6. FORECAST OF BREAKING WAVES DANGEROUS TO NAVIGATION FOR SPECIFIED SEA AREAS.

We have an extensive literature from all over the world on the subject of the mysterious disappearances of ships, both large and small. A high percentage of these mysteries can be solved by even a cursory study of freak waves, as it is sometimes performed by insurance companies. From their reports freak waves seem to occur on most continental shelves in the world during certain predictable times of the year. Their origin is not yet fully understood but it is belived that a shoaling mechanism, unique to a certain geographic location as well as an interaction between the large wind waves and an opposing coastal current combined with a particular random phase relationship between the waves can account for the phenomena. Known areas of destructive waves are the Nova Scotia coast, the Bermuda rise, the waters off Greenland, the coast of North West India and the waters off the South East African coasts, where the Agulhas current opposes the main disperison direction of the waves. The meeting with an extreme wave can be disastrous even for a quite large ship. On the 19th of september 1979 the norwegian 499 GRT roll-on roll-off ship "AUSTRI" was on voyage from Svelgen to Poland with a cargo of iron barrels. In the rather narrow navigational passage outside Slettringen at Sognefjord the ship was suddenly hit by a large wave breaking over the bow and starboard side. The ship got a heelling angle of near 30°, but before it could restore, it was hit by a new wave from another direction.

The result was that the ship got a very large heelling angle near 40° and then the cargo shifted. The ship was left by the crew and no emergency calls were send out. Shortly after the rescue float capsized in the surf near the shore and 5 people were lost. The ship containing the cargo that had shifted, was in fact quite stable, and maintaining an angle of heel near 80° it was drifting and turning until it finally was striking on a rock near the shore and broke into two parts. There it was found by the Court of Inquiry, see Fig. 21 and Fig. 22.

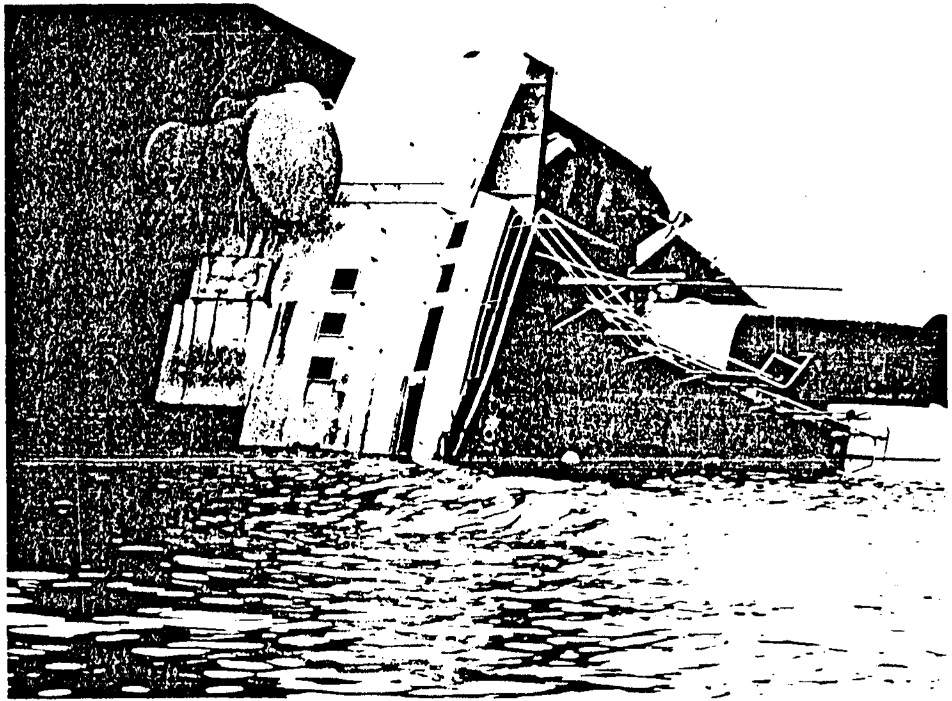


Fig. 21. "AUSTRI" capsized by the waves and broken into two parts.

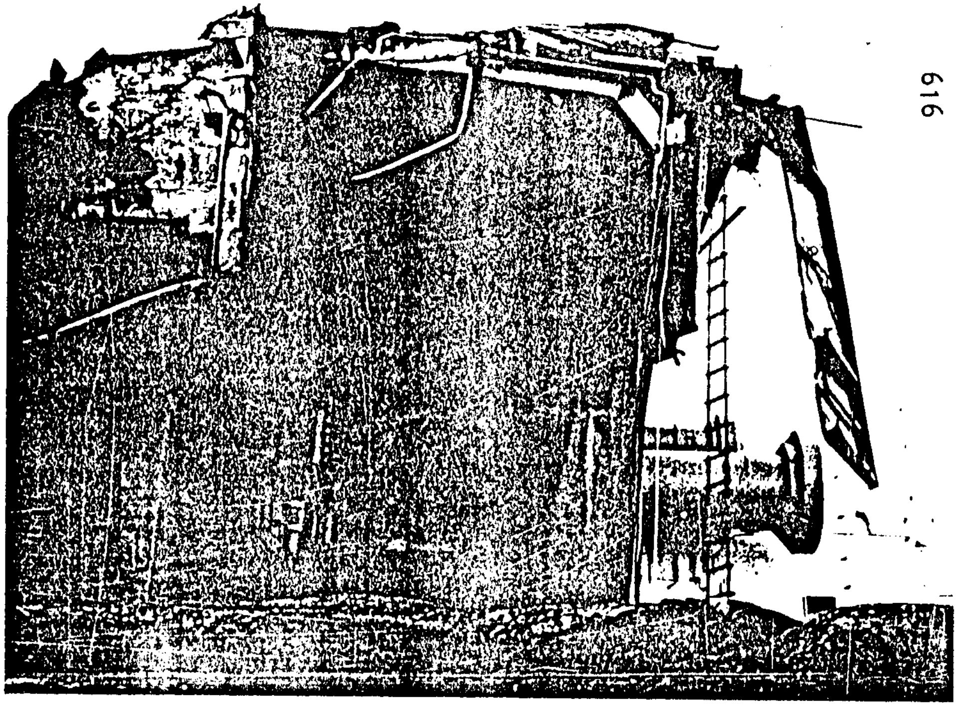


Fig. 22. "AUSTRI" broken into two parts. The engine in the center is part of the cargo.

The court of Inquiry came to the conclusion that the ship came into a topographic wave refraction area, and there was caught in a centre for focusing of rather large waves coming from different directions, see Fig.23.

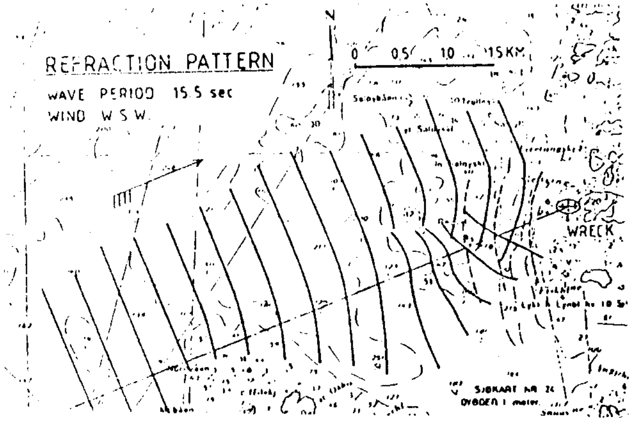


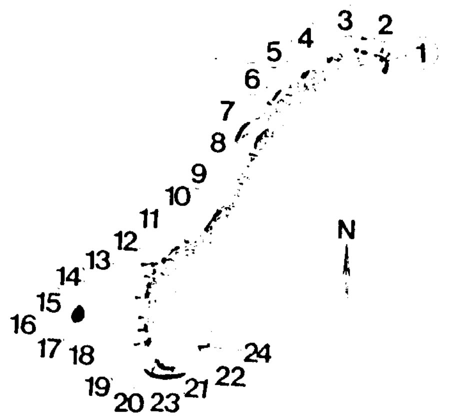
Fig. 23. Wave refraction pattern and the wreck of "AUSTRI". (From The Court of Inquiry's report prepared for the Norwegian Maritime Directorate.)

Further, the Court of Inquiry concluded that the ship might have been saved, if it had avoided this particular area and instead chosen a route in deep water. The Court of Inquiry further recommended that the extension off all such particular exposed areas, where such wave focusing effects are present, either due to a special topography or due to the refraction of large waves by currents, or combinations of these two, should be printed on the Navigational Charts for Norwegian waters, and this will now take place.

The large research project "SHIPS IN ROUGH SEAS" mentioned earlier in section 2, was initiated by the unusual high frequency of capsizing accidents on the Norwegian Continental Shelf. The part of this project concerning research on wave action had the final scope to develop a scheme, that incorporates a prediction of probabilities for extreme steep waves and breaking waves dangerous to navigation in the operational wave forecast for the Norwegian Continental Shelf for certain specially exposed areas. The main conclusions from the environmental analysis of the wave climate, the frequency of accidents, and their location along the Norwegian Coast was then the following:

"A certain number of exposed areas (alltogether 24) have been identified on the Norwegian continental shelf where the probability of occurrence of extreme waves and breaking waves is most pronounced. Most of these areas can be classified as parts of the shelf and coastal waters, where gravity waves influenced by topographic effects interact with a strong current. Wave refraction calculations have now confirmed that these areas have a focusing of wave energy during certain weather conditions. Forecast of dangerous, severe, steep and breaking waves in the 24 local areas are possible, based on the simultaneous exceedance of critical threshold values for wave direction and significant wave height, as it can be calculated from certain reference points."

The 24 exposed areas are shown in Fig. 24. A final proposal for such a new forecasting scheme is worked out, and handled over to Norwegian Authorities. (see KJELDSEN, LYSTAD, MYRHAUG 1981)



Nr	1	VARDO
"	2	TANAFJORDEN
"	3	NORDKINN
"	4	BREISUNDET
"	5	LOPPHAVET
"	6	SVEINGRUNNEN MALANGSGRUNNEN
"	7	LOFOTEN
"	8	VESTFJORDEN
"	9	FOLLA
"	10	GRIPHOLEN
"	11	HUSTADVIKA
"	12	GODO
"	13	STADT
"	14	BUEFJORDEN
"	15	SOGNESJOEN
"	16	VIKINGBANKEN
"	17	SLETTA
"	18	SKOTAMEDGRUNNEN
"	19	SIREGRUNNEN
"	20	LISTAFJORDEN
"	21	LISTA
"	22	RYVINGEN
"	23	SKAGERAK VEST
"	24	FÆRDER-TVISTEIN

Fig. 24. Exposed areas on the Noregian Continental Shelf. The accident with "AUSTRP" was in area No. 15.

7. MAPPING OF RESPONSES AND CALCULATION OF PROBABILITIES FOR EXTREME WAVES

The responses of ocean systems to extreme freak waves is most important and in particular the kinematics and local interior accelerations in such waves are important for the ultimate wave loads and movements that might be observed LONGUET-HIGGINS & COKELET 1976 calculated the interior particle kinematics and accelerations for steep non-linear Stokes waves that was forced to break as plunging breakers in deep waters. Using a numerical simulation they found local particle velocities in the tip of the jet as high as 2.5 times the linear phase velocity, while local accelerations in these waves below the developing jets could attain values in the range 3-5 times the gravity acceleration. The local particle kinematic velocities has then to be squared, when drag forces in such waves are evaluated. For this reason, measurements of the local particle kinematics in the crests of deterministric freak waves, breaking as plunging breakers, was measured at NHL. As no reliable recording instruments for measurements of wave kinematics in a mixture of entrained air and water in the crest of breaking waves were available, a zero-density tracer particle technology combined with a high-speed frame to frame film analysis, were used for this particular purpose. Results of such measurements are shown in Fig. 25.

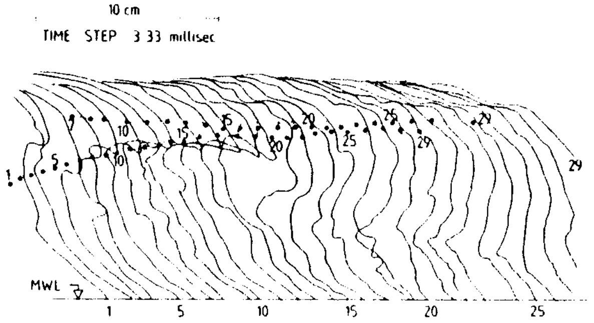


Fig. 25. Particle trajectories in the crest of a breaking freak wave. (From KJELDSEN, VINJE, MYRHAUG, BREVIG 1980).From these measurements local particle velocities as high as 2.8 times the wave phase velocity were obtained, and this therefore confirms the predictions made by LONGUET-HIGGINS & COKELET 1976.

Another kind of most interesting results that can be obtained from laboratory simulations of extreme freak waves, is the evidence of certain rare dynamic effects from such waves on ocean systems such as slamming loads, shock pressures and snap loads in mooring lines. For such investigations the particular wave generation technique for extreme waves, is most usefull, and superior to all other techniques, because the generated plunging breakers can be transferred slightly up and down in the wave flume, in a way that makes it possible to optimize test conditions and to make a very direct strike on the system installed for testing. An example of shock pressures measured on a fixed plate tilted 45 degrees and striked from below by deep water spilling breakers is shown in Fig.26.

The mean shock pressure is here plotted as a function of the steepness ratio ε/s, where ε is the crest front steepness of the wave, and $s = H \cdot g/2\pi \cdot T_{zd}^2$ is the total stepness of the wave. In periodic waves this particular steepness ratio can be taken as a measure of the non-linearity of the waves. $\varepsilon/s = 2$ corresponds to sinusoidal waves. Wave breaking occurs approximately at $\varepsilon/s = 3.5$. The horizontal asymmetry factor μ for the breaking waves is used in the normalisation of shock pressures. The factor $\rho g \mu H$ corresponds to the hydrostatic pressure at mean water level for a water column reaching crest height level in an asymmetric wave. The Figure shows shock pressures in excees of hydrostatic pressure. Thus $\rho g(H\mu - z_i)$ is the hydrostatic pressure at transducer No i, elevated z_i above the mean water level, while p_{si} is the mean value of shock peaks resorded by transducer No i. The overall conclusions from this tests were that mean values of dynamic shock pressures increased, with an increasing value of the wave steepness ratio ε/s. (See KJELDSEN 1981). It thus seems, that plotting of measured responses of various kinds related to the wave asymmetry parameters defined in section 3, might lead to an improved understanding of the physics in the phenomena under investigation.

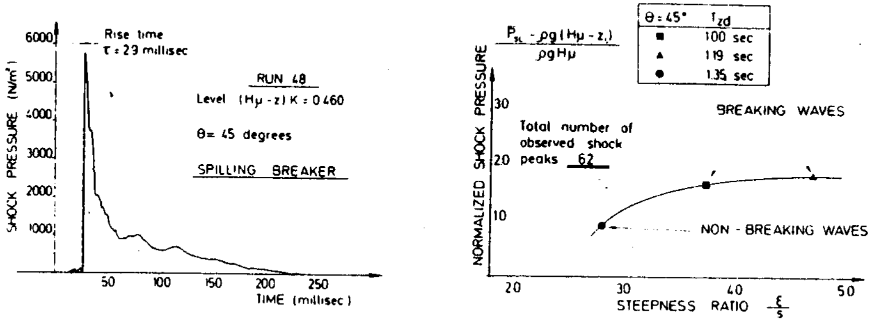


Fig. 26. Example of shock pressures recorded on a tilted plate in deep water spilling breakers. (From KJELDSEN 1981).

We shall now turn to the very essential part in the design philosophy as it is shown in Fig.1 namely the estimation of the probabilities of the particular deterministic freak wave situations that has been chosen for testing. Such an evaluation is based of the type of diagram showed in Fig. 27.

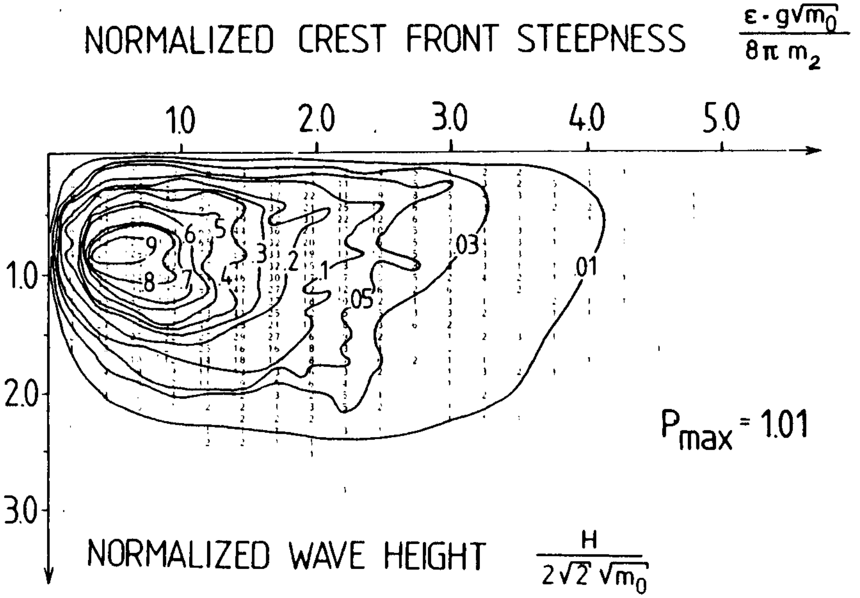


Fig. 27. Joint probability density distribution of crest front steepness and zero-downcross wave height. (From KJELDSEN & MYRHAUG 1980).

This is an example of the joint probability distribution for normalised crest front steepness and zero-downcross wave height containing not less than 6353 individual waves. This distribution was established as a part of the work performed in the project "SHIPS IN ROUGH SEAS". 22 gales containing a total of 25.000 waves occurring on the Norwegian Continental Shelf were analysed, and these time series containing extreme waves were selected for the joint probability distribution given above. It can thus be somewhat on the conservative side to present the distribution after this selection. On the other hand the Waverider buoys with which the data were obtained is known to distort the measurements and produce signals, that contains less non-linearity then the sea surface itself. Thus, we have a fair first estimate of probabilities for large freak waves based on joint probabilities for simultaneous exceedence of threshold limits both in wave height and in crest front steepness of individual waves. The joint probability distribution given in Fig. 27 is unique, as it contains data from many sea states, normalised with respect to the moments m_0 and m_2 in the respective wave spectra.

However when an extreme response on an ocean system is encountered, there is a third wave parameter to take into account in addition to wave height and steepness and that is the coherence along the crest of the waves, or as it also can be obtained, the synoptic length of the wave crests in a 3-dimensional short-crested sea. For such a sea the mean value of the wave crest lengths can be found directly as:

$$\bar{L}_{crest} = \sqrt{1 + n} \cdot E\left\{\sqrt{\frac{n}{1+n}}\right\} \bar{\lambda} \qquad (7.1)$$

where E ( ) is the Legendre's complete elliptic integral of the first kind. λ is the mean synoptic wave length given as:

$$\lambda = 2\pi g \sqrt{\frac{m_0}{m_4}} \qquad (7.2)$$

and n is the spreading factor in the representation of a directional wave spetrum given as:

$$\phi(\omega, \theta) = A_n \cdot \cos^n \theta \cdot \phi(\omega) \qquad (7.3)$$

Here the assumption is made that wave energy propagation is distributed equally in all directions at all frequencies. Values recommended for use with one-dimensional ITTC and ISSC spectra $\phi(\omega)$ are then:

$$n = 2: \quad A_n = \frac{2}{\pi} \qquad (7.4)$$

$$n = 4: \quad A_n = \frac{8}{3\pi} \qquad (7.5)$$

Thus, with assess to measurements or assumptions regarding the directional wave spectrum, mean values of wave crest lengths can be obtained directly. Thus, the kind of diagram that rearly represents the severity of extreme waves as they can be encountered in a 3-dimensional sea, is a 3-dimensional joint probability distribution where crest lengths normalised with respect to mean synoptic wave length are given on one axis, while crest front steepness and zero-downcross wave height normalized with respect to the moments in the wave spectrum are given on the other 2 axes see Fig. 28. With such a representation the coherence along the wave crests is incorporated in the description of severe freak waves. This means that a 2-dimensional description of wave kinematics in the way it is simulated by LONGUET-HIGGINS & COKELET 1976 or in the way it is measured and shown on Fig. 25, might be used together with a calculated finite crest length, as it can be obtained directly from Eq (7.1). The practical importance of such calculations is evident. One example is a ship encountering a plunging breaker in a beam sea, where most often the wave crest length will be less then the total length of the ship. This was the case with "AUSTRI" as mentioned in section 6.

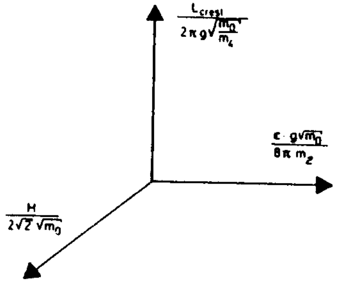


Fig. 28. 3-dimensional joint probability distribution.

However, for simulation of a directional wave spectrum in a wave basin one complicati exist, namely the fact that the high frequency part of the real wave spectrum is cut of Mechanical wave generators in most hydrodynamic laboratories usually have a higl frequency limit for performance at 2Hz. This means that all moments in the spectrum m m_2 and m_4 are distorted and this implies that it is not physical possible to obtain directional wave spectrum that matches a prescribed wave spectrum, and at the sar time obtain prescribed values of significant wave height, average wave period, averag synoptic wave length and average crest length. The result is that tests with truncate spectra should be devised. An example of a truncation of a one-dimensional wav spectrum is given by TAKEZAWA 1981, see Fig. 29.

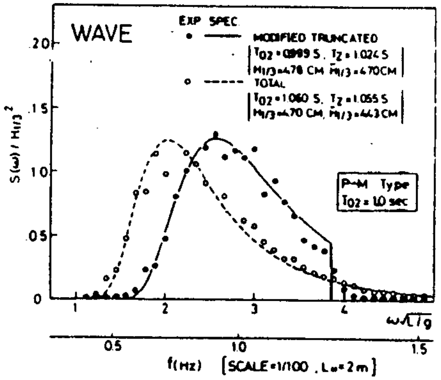


Fig. 29. One-dimensional truncated wave spectrum. (From TAKEZAWA 1981).

A truncation of a directional wave spectrum to be simulated in the large sea simulating basin can then be prescribed directly using Fig.30. The moment m_4 is most important for evaluation of the synoptic properties of the sea. However, for the PIERSON-MOSKOWITZ wave spectrum this moment is given as:

$$m_4 = \frac{A}{4} \cdot \Gamma(0) \qquad (7.6)$$

where Γ ( ) is the Gamma function.

We can therefore conclude, that this moment only can be defined when a proper truncation factor r is prescribed in the definition given as:

$$r = \frac{T_{cut\text{-}off}}{T_m} \qquad (7.7)$$

where $T_{cut\text{-}off}$ is the cut-off wave period and T_m is the modal period. Calculations of wave crest length with proper account to the wave truncation factor for JONSWAP and PIERSON-MOSKOWITZ wave spectra are given by KJELDSEN & PRICE 1982 and an example is shown in Fig. 30.

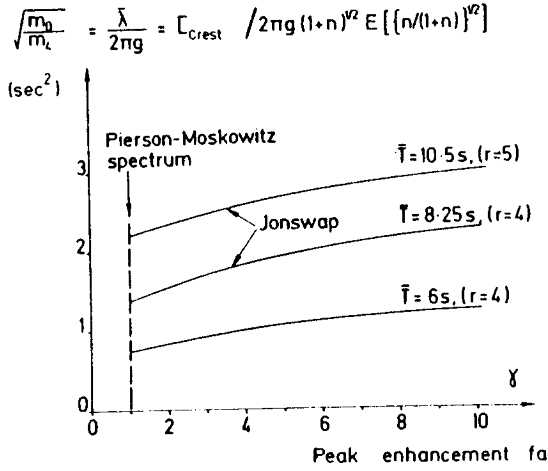


Fig. 30. Calculation of mean crest lengths based on PIERSON-MOSKOWITZ and JONSWAP-spectra with truncation factors r=4 and r=5. (From KJELDSEN & PRICE 1982).

TOKI 1982 performed a numerical simulation of JONSWAP and ISSC-spectra and mapped simulated values of the wave asymmetry parameters ·, λ and μ . As design waves for floating structures either for model testing or for numerical simulation TOKI then recommended a wave that had a maximum wave height and an exceedance probability of 1/10 on the value of the crest front steepness. The diagrame presented in the present study in Fig. 27 is rather unique, in that aspect that it is the only published result giving the joint probability of the crest front steepness and the wave height for single zero-downcross waves. However, it is hoped, that other naval architechts and engineers will adapt this basic idea, shown in Fig. 27 that the severity of a given sea state not can be evaluated from the wave height alone. The diagram presented in Fig. 27 was measured in deep waters on the Norwegian Continental Shelf at 3 different locations. It is the hope that others will establish the same kind of diagram in shallow waters, as well as in deep waters in other parts of the world for comparisons, and in a continuation of the ideas presented here, plot measured or simulated responses on ocean systems in this kind of diagrams.

The idea of plotting extreme responses encountered by ocean systems, using the wave asymmetry parameters in the time domain, is actually an application of the half-cycle counting technique already in use for wave slamming analysis.

8. CONCLUSIONS

1) Severe rare responses of ocean systems such as extreme movements, slamming loads, shock pressures, high mooring loads and snap loads can be analysed in the time domain and plotted as function of wave asymmetry parameters. This way of analysing responses is an extension of the half-cycle counting technique already in use for wave slamming analysis. Analysis of severe rare responses occurring either on vessels or ocean structures in operation, in experiments performed in the laboratory, or in numerical experiments, will provide the profession of knowledge, to further identify and detail severe situations suited for an efficient deterministic testing, of such structures in hydrodynamic laboratories.

2) A number of situations both for smaller vessels and for ocean systems in general are now identified as leading to significant responses, and is therefore suited for efficient deterministic experiments in addition to the traditional testing in prescribed linear wave spectra.

3) Much greater realism using modern wave simulator technology can now be achieved for testing of vessels and ocean systems in 3-dimensional seas. It is now possible to generate in the laboratory any prescribed deterministic wave or wave train, appearing at a prescribed time and position in a wave basin and if arranged, also breaking in a prescribed mode, such as plunging, spilling or progressing like a bore. The obtained 3-dimensional extreme waves represents a close approximation to the maximum wave height that might be obtained in a given directional wave spectrum with all the physical restrictions and all the non-linear effects from wave interaction present. Thus it represents an alternative choice, to the 100-year design wave obtained from an often uncertain mathematical extrapolation of limited field data from a short period of years.

4) Severeness of a sea state containing large breaking waves dangerous to the navigation of smaller vessels, can not be assessed using information about wave heights alone. It is only the joint exceedances of threshold limits for crest front steepness and zero-downcross wave height that turns out to be important for safety against capsizing. Another important parameter to consider is the crest length of a breaking wave.

5) A proposal for forecast of large breaking waves dangerous to navigation in 24 specially exposed areas along the Norwegian Coast is worked out and submitted to Norwegian Authorities.

9. ACKNOWLEDGEMENT

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