Public Summary CresT JIP

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Introduction

In the offshore and shipping industry, extreme wave events have attracted a lot of attention in the last decade. This was stimulated a lot by the recording of the extreme 'New Year Wave' on the Draupner platform on 1 January 1995. As reported by Haver (2000), it had a wave height of 25.6m and crest elevation of 18.5m in an underlying sea-state of significant wave height of only 11.94m, see Figure 1.

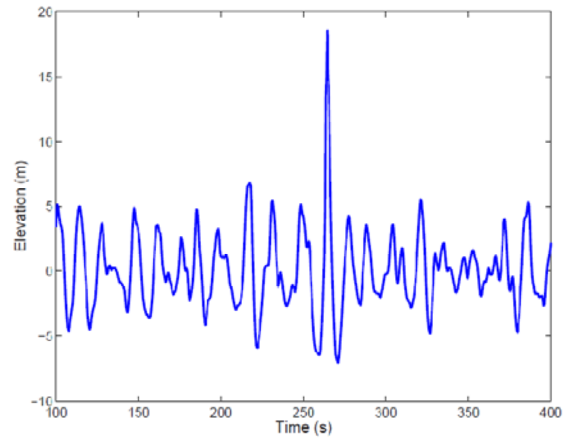

Figure 1. The 'New Year Wave' on the Draupner platform on January 1, 1995

Also in basin experiments and numerical methods extreme events have been reported and studied. Figure 2 gives an example from basin experiments by Buchner et al (2007), showing an extreme wave as it progresses along 6 wave probes (positioned over less than a wave length distance). The rapid increase of the crest height is evident. An extensive research line on the background of this behavior has been conducted by Swan and his students (see [4] and Gibson and Swan, 2007).

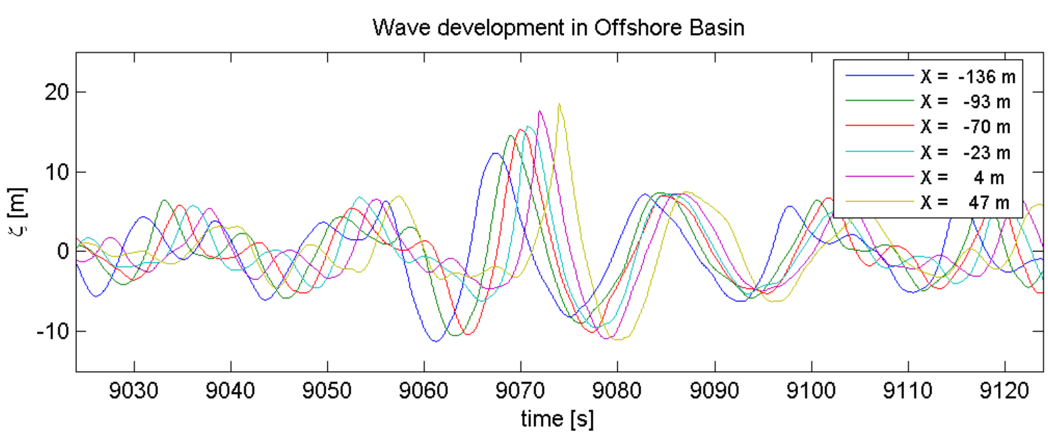

Figure 2. Development of an extreme (long crested) wave in a model basin

Obtaining further insight in extreme waves and their impact required a strong cooperation between metocean specialists, wave modelling experts, hydrodynamicists and reliability specialists. This is why the CresT (Cooperative Research on Extreme Seas and their impacT) Joint Industry Project has been carried out.

The objective of the CresT JIP was 'to develop models for realistic extreme waves and a design methodology for the loading and response of floating platforms'. Within this objective the central question was: 'What is the highest (most critical) wave crest that will be encountered by my platform in its lifetime?'

To address this question, the scope of work for the CresT JIP was divided into five work packages:

- WP1 (Numerical spectral wave modeling of extreme sea states) by Vince Cardone (OceanWeather): WP1 provided realistic 2D wave spectra in which extreme waves can occur (including short-crested and crossing seas).
- WP2 (Analysis of field and laboratory wave statistics) by Kevin Ewans and Marios Christou (Shell Int E&P) and George Forristall (Forristall Ocean Engineering): WP2 analyzed real and basin waves to determine whether extreme waves can be identified (also beyond second order). Also their relation with specific 2D wave spectra (and other conditions) was investigated.
- WP3 (Deterministic and probabilistic extreme wave modeling) by Chris Swan (Imperial College) and Peter Tromans (Ocean Wave Engineering): WP3 provided physical explanations for these waves, their kinematics and their short-term statistics.
- WP4 (Wave loading and response) by Bas Buchner and Janou Hennig (MARIN): WP4 performed the model tests (waves only and waves with structure) and determined the dynamic loading and response as a result of these extreme waves (both local loading and global response).
- WP5 (Risk and reliability) by Elzbieta Bitner-Gregersen and Oistein Hagen (DNV): WP5 put the work in the overall perspective of the risk analysis and design of a platform.

At the end of the CresT JIP a lot of work has been done and reported by all research partners. This document summarizes the findings in these reports in the light of the central question and provides a recommendation on the use of a probability distribution function based on the CresT results.

Some basic notes on wave theory

Extreme wave theory is extremely complex and still undergoing strong development. As part of this summary document it is not possible to give a good summary of the present state-of-the-art in this field. For a real thorough treatment, reference is made to Swan and his students ([4] and Gibson and Swan, 2007) and Tromans [5]. However, it seems important to make some basic notes on the theory as a guide to the further document.

The first note relates to the description of the ocean surface as a 'sum of sines' as it is generally considered by naval architects and offshore engineers, see Figure 3. The irregular surface elevation at one location is considered to be the sum of a large number of regular sinusoidal wave components with different frequencies and amplitudes. This is also the way they are transformed through Fourier analysis into a wave spectrum.

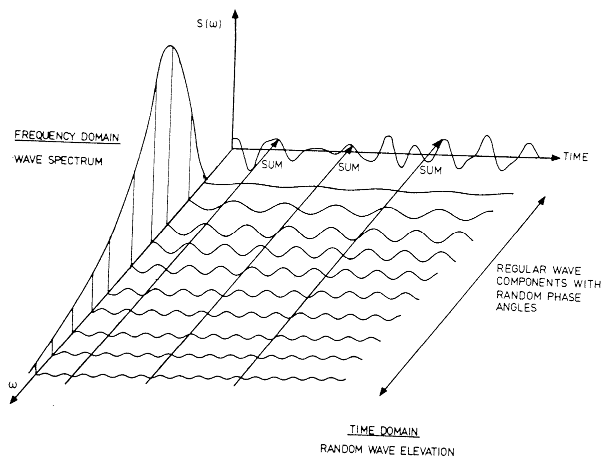

Figure 3. Modelling of an extreme (long crested) wave in a model basin

Although any irregular signal can be represented as a spectrum through Fourier analysis, in a (linear) wave representation it is also assumed that the inverse process is allowed to generate a realistic surface description: from a wave spectrum an irregular wave signal is generated based on the amplitudes of the spectrum and a random phase between the different frequency components. However, it is very important to realise that this is based on the *linear* assumption that there is no interaction between the different frequency components so that they can simply be summed up.

This linear assumption holds true for a large part of the wave field. However, in areas where the waves are getting higher (through linear wave grouping), non-linear processes start to play a role because locally the waves become steeper. The well-known second order effect is an example of such effect: the crest heights are getting higher and the troughs are getting less deep, so we get vertically assymmetric waves. Quadratic (second order) effects start to play a role in the physics, giving interactions between the different frequencies in the wave, so that they are no longer independent as assumed above. Two different wave frequencies start to interact through the sum of their frequencies (high frequency effect) and the difference of their frequencies (low frequency effect). Apart from the complex hydrodynamic components in the resulting expression (simplified as A_{ij} and B_{ij} below), one will recognise the classic form of the square of two sinusoidal signals in the expression below (from Gibson, 2007):

$$\begin{aligned}\eta(x,t) &= \sum_{i=1}^{N} a_i \cos(k_i x - \omega_i t) && \textit{linear term}\\ &+ \sum_{i=1}^{N}\sum_{j=1}^{N} A_{ij} a_i a_j \cos([k_i + k_j]\,x - [\omega_i + \omega_j]\,t) && \textit{sum term}\\ &+ \sum_{i=1}^{N}\sum_{j=1}^{N} B_{ij} a_i a_j \cos([k_i - k_j]\,x - [\omega_i - \omega_j]\,t) && \textit{difference term}\end{aligned}$$

On top of the dominant linear underlying signal, we recognize the high frequency sum frequency and low frequency difference frequency. All are clearly visible in the plot in Figure 4 (from Stansberg, 1989) based on the theory developed by Sharma and Dean (1981):

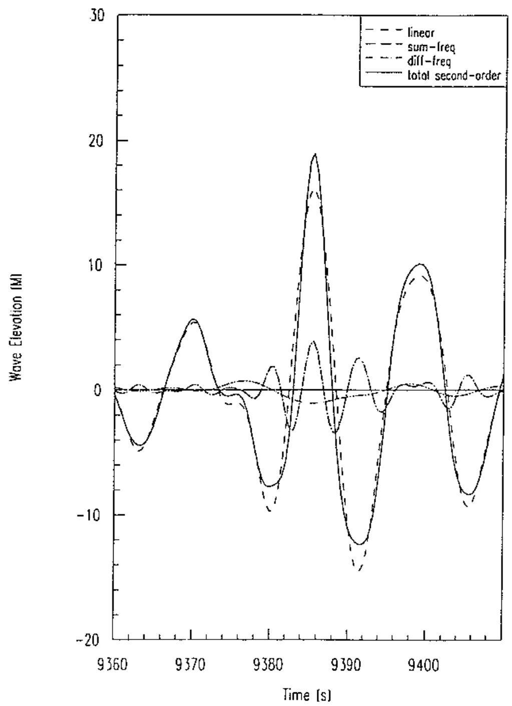

Figure 4. Development of an extreme (long crested) wave in a model basin

We call this second order effect a 'bound' wave effect as it travels with the wave and develops (growths and disappears) with the underlying linear wave (it does not have 'a life of its own' and depends on the 'mother' linear wave). Second order statistics, such as Forristall (2000), are based on this type of considerations and methodologies and are an important improvement compared to linear theory.

However, wave physics do not stop at quadratic second order effects and at higher order the situation becomes extremely complex: the number of interacting wave components (2 in second order, 3 in third order, …) increases rapidly. For a good treatment of the related mathematics, reference is made to Swan and his students ([4] and Gibson and Swan, 2007) and Tromans [5]. For the purpose of this summary it is important to realize that the following applies when we include third order effects:

- Wave components are not independent, but interacting
- This interaction (non-linearity) is the strongest in steep wave events that can occur through focusing of the underlying linear wave (for the rest of the sea state or wave field the interaction is low and slow)
- At that moment (near) resonant wave-wave interactions can occur: the combination of 3 wave components can result in a new wave that has its characteristics (wave frequency and wave length) at (or close to) the linear dispersion relation ($\omega^2 = gk$ for deep water). This allows this new wave to behave as a normal free wave ('resonate'), which can result in rapid exchanges of energy within the wave spectrum (between the frequencies). Rapid changes in the waves and high extremes can be the result. Mathematically this can be presented as (Gibson, 2007):

$$\begin{aligned}\eta_{crest} &= \sum_i f(A_i) \quad \textit{(free)} \quad + \sum_i \sum_j g(A_i A_j) \quad \textit{(bound)} \\ &+ \sum_i \sum_j \sum_k h_b(A_i A_j A_k) \quad \textit{(bound)} \quad + \sum_i \sum_j \sum_k h_r(A_i A_j A_k) \quad \textit{(resonant)}\end{aligned}$$

Beside this non-linear dispersion occurs: higher waves travel faster than small waves.

Figure 5 gives an example from his work for the resulting wave crest (linear, second order and third order):

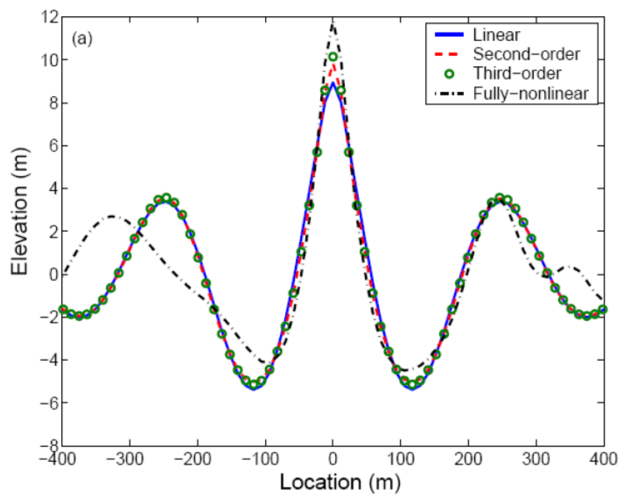

Figure 5. Wave crest simulated with linear, second order and third order theory

We will now discuss how these non-linear effects affect the wave height and crest height distributions in long and short crested conditions in numerical simulations, model tests and field data.

Long-crested waves

Theory

Non-linear effects, such as third-order resonant interactions in long-crested waves, modulate the waves. These effects have been predicted by various theoretical approaches, including the nonlinear Schrödinger equation, the Dysthe equation, the Zakharov equation, and the fully nonlinear simulations by Swan and his students.

A summary of Swan's work is given in [4]. Figure 6 shows his calculations for a unidirectional JONSWAP spectrum and contrasts the distribution of wave crests based upon a linear (Rayleigh) distribution, a second order distribution (Forristall, 2000), numerically simulated data, and the results of the spectral response surface method (SRS) in which the wave calculations are based upon the fully nonlinear wave model outlined in the fully nonlinear model described by Bateman, Swan & Taylor (BST). This Figure shows that in long-crested seas, with a large peak enhancement factor of γ=5, large nonlinear increases occur in the crest elevation beyond that predicted at second-order. The explanation has its origins in the third-order resonant interactions.

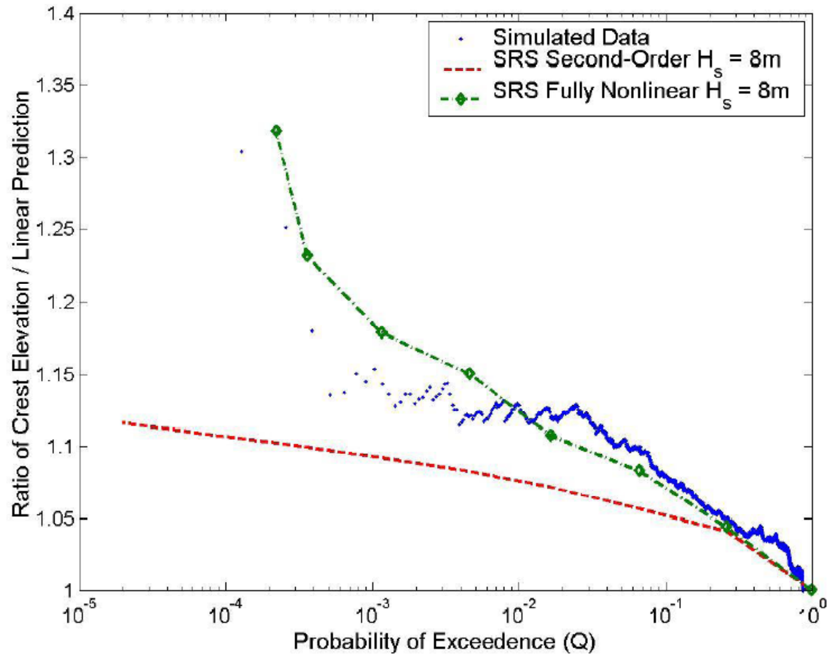

Figure 6. Simulations of crest height in a long-crested sea (from [4])

This is confirmed in the CresT project by the work on the Zakharov equation by Tromans [5], shown in the Figure 7 below. In this figure there are three sets of results from earlier work by Gibson et al [2007]: the dashed red line is the result of second order theory, the blue dots are from a time domain simulation and the green line uses a probabilistic calculation similar to the present one, but coupled with numerical simulation of the crest evolution. Both of the last two are based on the fully non-linear model of Bateman. The new Tromans results are superposed as red spots.

All of these calculations show crest heights at low probabilities that are much higher than those predicted by second-order theory.

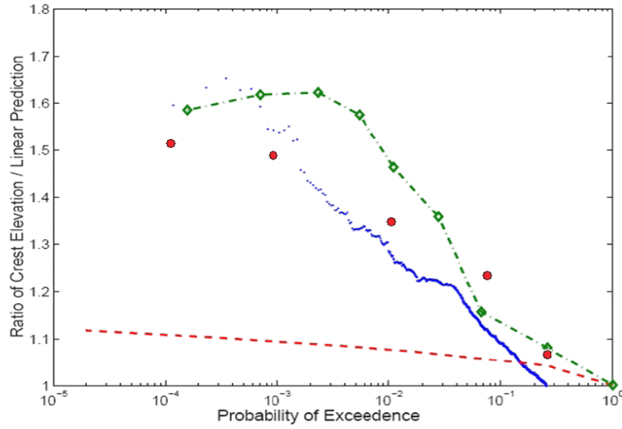

Figure 7. Crest height distributions in a long-crested sea calculated from the Zakharov equation (from [5]). The dashed red line is second order theory, the blue dots are from a non-linear time domain simulation and the green line uses a probabilistic calculation. The new Tromans results are the red spots.

Wave Basin Measurements

The numerical results are confirmed by the basin tests at Imperial College and MARIN. An example from the Imperial College tests is given in Figure 8 (UD in the Figure indicates uni directional waves). As reported by Swan [4]: 'The crest height distributions suggest that for exceedence probabilities larger than 10^{-3}, the measured crest elevations are larger than those predicted by a second-order distribution. The increase in crest elevation above the second-order prediction being a maximum of 10% and always less than the difference between the linear and the second-order solutions. (…) For exceedence probabilities less than 10^{-3}, the distribution of wave crest elevation reduces below that predicted by a second-order model. This appears to be associated with the onset of wave breaking, typically wave spilling.'

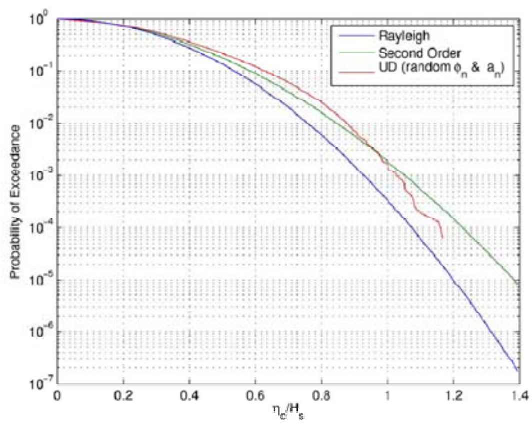

Figure 8. Crest height distribution observed for long-crested (Uni Directional) seas in the Imperial College basin (from [4])

The waves in Figure 8 were within one wavelength of the wave generator. The results are very similar to the results in the MARIN Offshore Basin at a similar distance from the wave generator as analyzed in detail by Forristall [3]. Example results are shown in Figure 9.

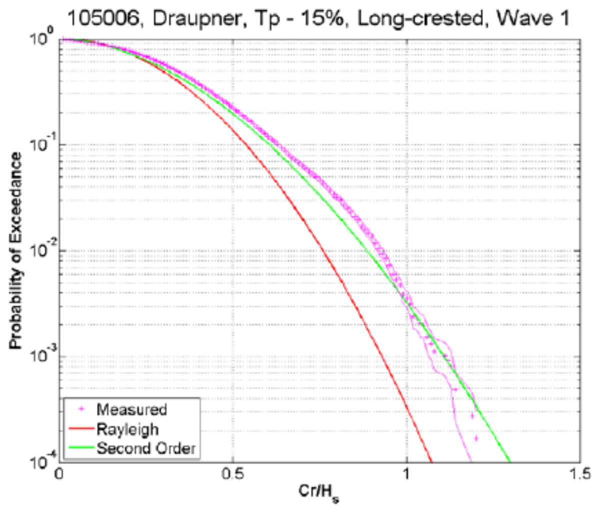

Figure 9. Crest height distribution observed for long-crested seas in the Marin Offshore Basin, 100m from wave flap (scale 1:50, from [3])

This effect of wave breaking as a limiting process is an important observation. However, when we follow the development of the wave over an increasing distance from the wave generator, we also see that breaking does not stop the further development of extreme crests. Figures 10 and 11 show crest height distributions for the same test as in Figure 9, but at greater distances from the wave generator.

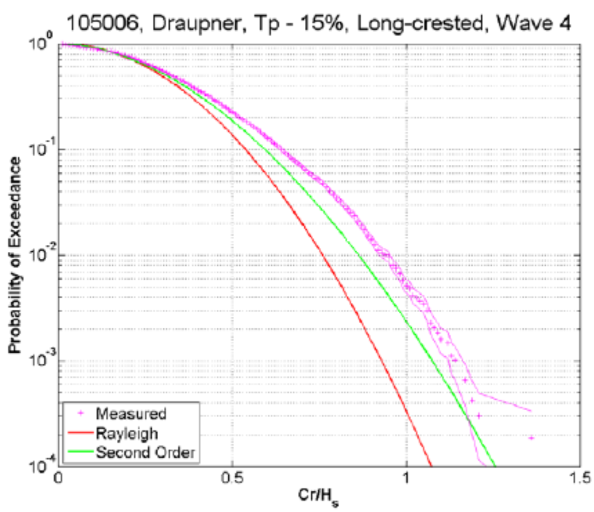

Figure 10. Crest height distribution observed in the Marin Offshore Basin approximately 2 wave lengths from the wave generator, 649m from wave flap (scale 1:50, from [3])

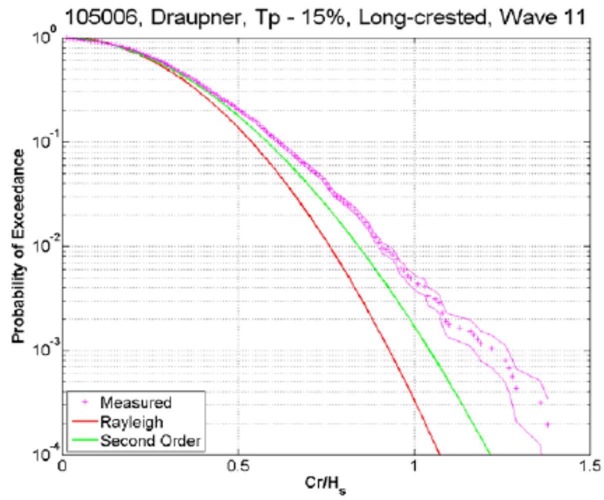

Figure 11. Crest height distribution observed in the Marin Offshore Basin approximately 5 wave lengths from the wave generator, 1930m from wave flap (scale 1:50, from [3])

These measurements show that the third-order resonant interactions in long-crested waves take a few wave lengths to modify the crest height distribution. This growth observed is somewhat faster than has been reported in some other studies, as the MARIN Offshore Basin is only 5-10 wave lengths long at scale 1:50. This is in line with the rapid changes due to third-order resonant interactions reported by Swan [4] and can also be observed in the power spectral density as reported by Christou et al (2008) using wavelet analysis of an extreme long crested wave event. In only 66m the spectral density changes completely with a clear shift to higher frequencies, see Figure 12.

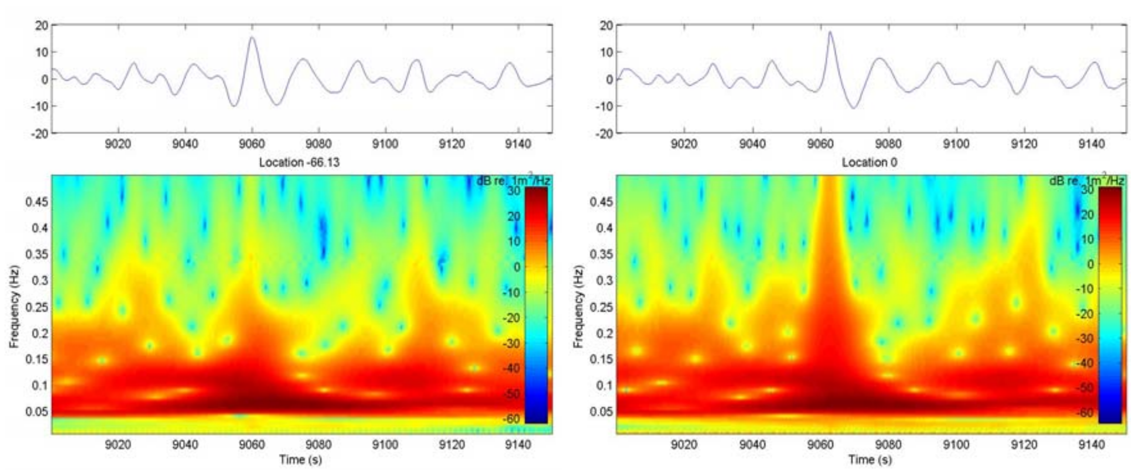

Figure 12. Rapid changes of the power spectral density between two locations: -66m from the extreme crest location (left) and at the extreme crest location itself (right), from Christou et al (2008). Top gives the time trace at the location, bottom the power spectral density as function of time.

The observation of the limiting effect of wave breaking on crest height development by Swan [4] has an interesting implication: non-linear effects in the extreme waves will only occur in steeper sea states.

However, the wave breaking will be stronger in the steeper sea states. So the development of extreme crests will be stronger in steeper sea states, but the process that limits them as well.

Short-crested waves

Theory

Numerical work by Swan [as summarized in 4] already showed the importance of short-crestedness (and spectral bandwidth) for the probability distribution of the extremes: 'Taken as a whole, it appears as if both the directionality of the sea state and its spectral bandwidth are the key factors in determining the extent of any nonlinearity [4]'. This is shown in the two cases presented in Figure 13. The first concerns a JONSWAP spectrum with a directional spread of s=7 or σ_θ=30˚ (the directionality applied uniformly to all frequency components). In this case the distribution of wave crests lies between the linear (Rayleigh) and the second-order distribution, with no evidence of wave crests exceeding the second-order distribution. The second example concerns a narrow banded Gaussian distribution, with a directional spread corresponding to σ_θ=5˚. In this, arguably unrealistic case, nonlinear increases in the distribution of wave crests beyond that predicted at second-order are again observed. These data suggest that whilst crest elevations larger than those predicted at second-order can indeed be predicted, both the spectral shape (particularly the spectral band-width) and the directional spread is critically important.

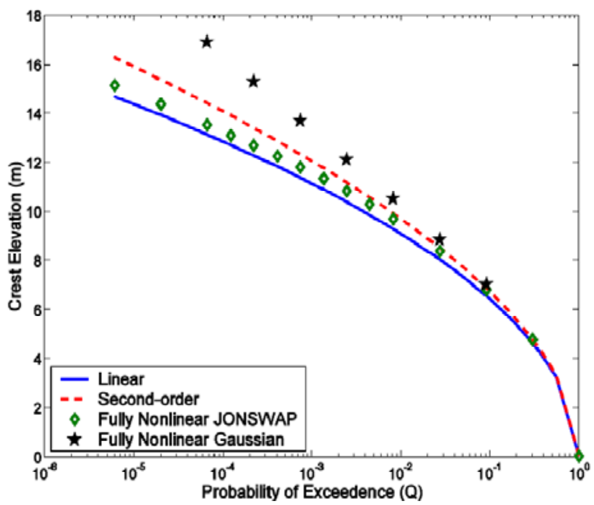

Figure 13. Simulations of crest height in a short-crested sea (from [4])

Tromans [5] analyzed the Zakharov equation to study short-crested seas. Figure 14 shows as an example the influence of the level of spreading (at probability of exceedance level 10^{-3}, compared to second order).

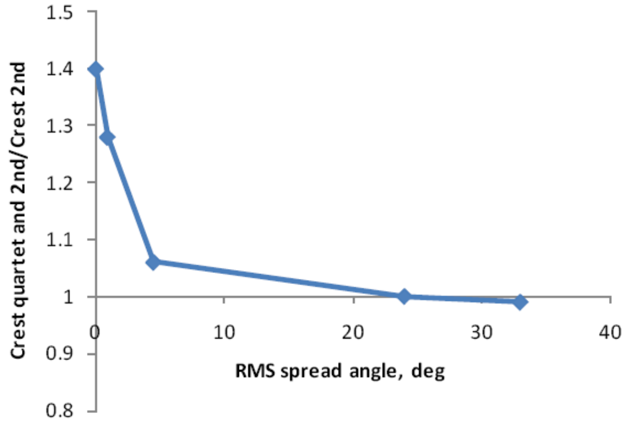

Figure 14. The influence of the level of spreading (relative to second order) for a sea state with H_s = 12m, T_p = 12.8s, γ = 5 (spreading varied by scaling, probability of exceedance = 10^{-3}).

Although these results are for only one sea state, the trend of reducing crest amplification with increasing spreading seems clear.

Wave Basin Measurements

The theory shows that the deviation from second order is much less in short-crested waves. This is confirmed in the basin test results at Imperial College and MARIN. First we show the MARIN results (Figure 15: long-crested, Figure 16: short-crested low spreading s=15, Figure 17: strong spreading s=4):

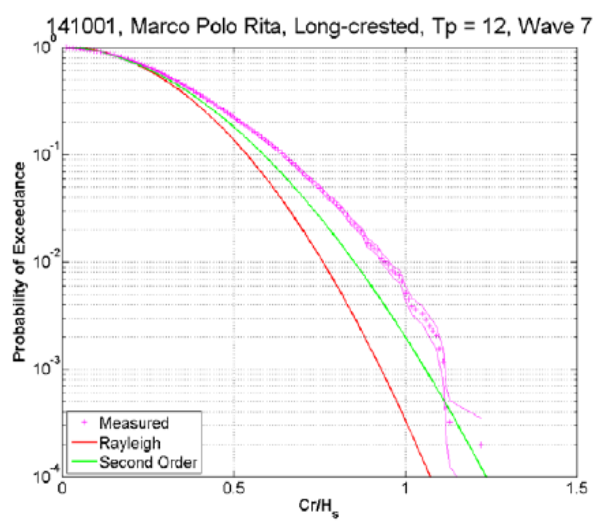

Figure 15. Crest distribution in the Marin Offshore Basin for long-crested waves in deep water (from [3])

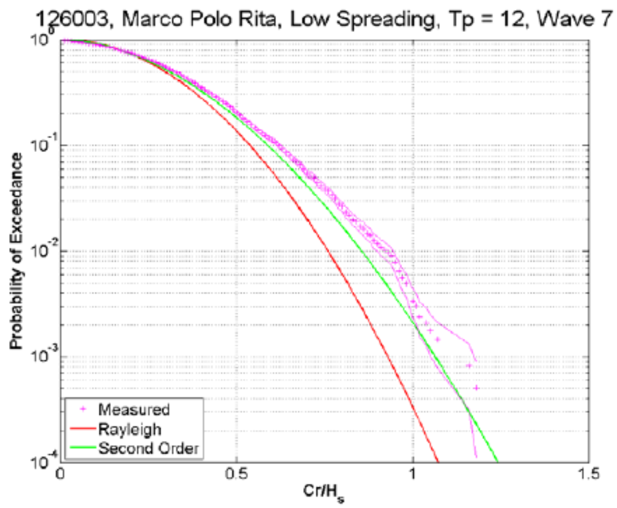

Figure 16. Crest distribution in the Marin Offshore Basin for short-crested waves with low spreading (s=15, from [3])

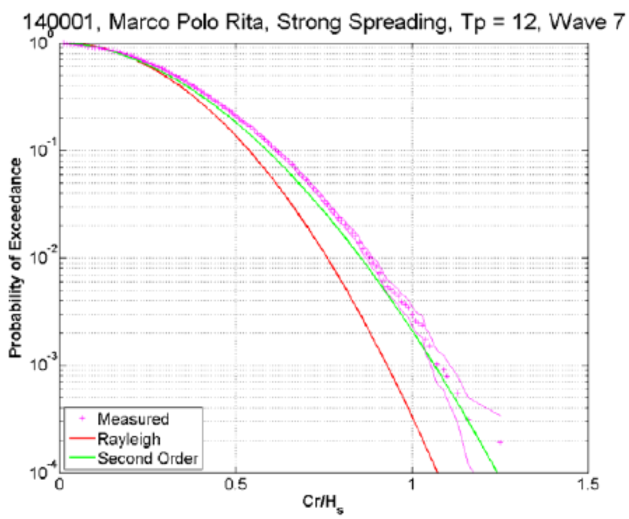

Figure 17.Crest distribution in the Marin Offshore Basin for short-crested waves with strong spreading (s=4, from [3])

The reduction of the deviation from second order with increasing spreading is clear from these plots. The results at Imperial College (Figure 18) show the same trend and also confirm another thing: the wave breaking that limited the growth of the most extreme crests in the long crested case, is reduced in the short-crested case as a result of the fact that the local short-crested waves are less steep. This allows a few of the short-crested waves to grow over a longer distance and so become larger.

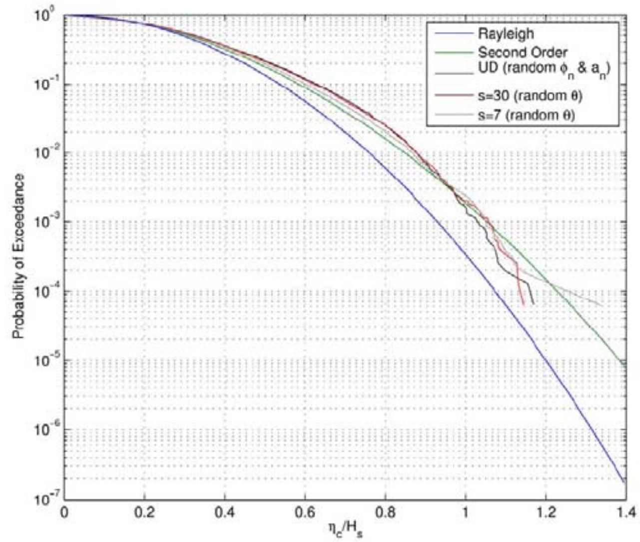

Figure 18. Crest distribution in the Imperial basin for short-crested seas (from [4])

Another interesting thing revealed by the tests at Imperial College is the sensitivity of the distribution for the sea state steepness. This is shown in Figure 19, where the distributions are presented (each representing 60 hours duration full scale) for a sea state with T_p=16s (γ=2.5, s=30) and three different steepness values of H_s=10m (3.7%), H_s=15m (5.6%) and H_s=20m (7.5%).

The steepness S1 is based on the mean period T1 according to [2]:

$$S_1 = \frac{2\pi}{g}\frac{H_s}{T_1^2}$$

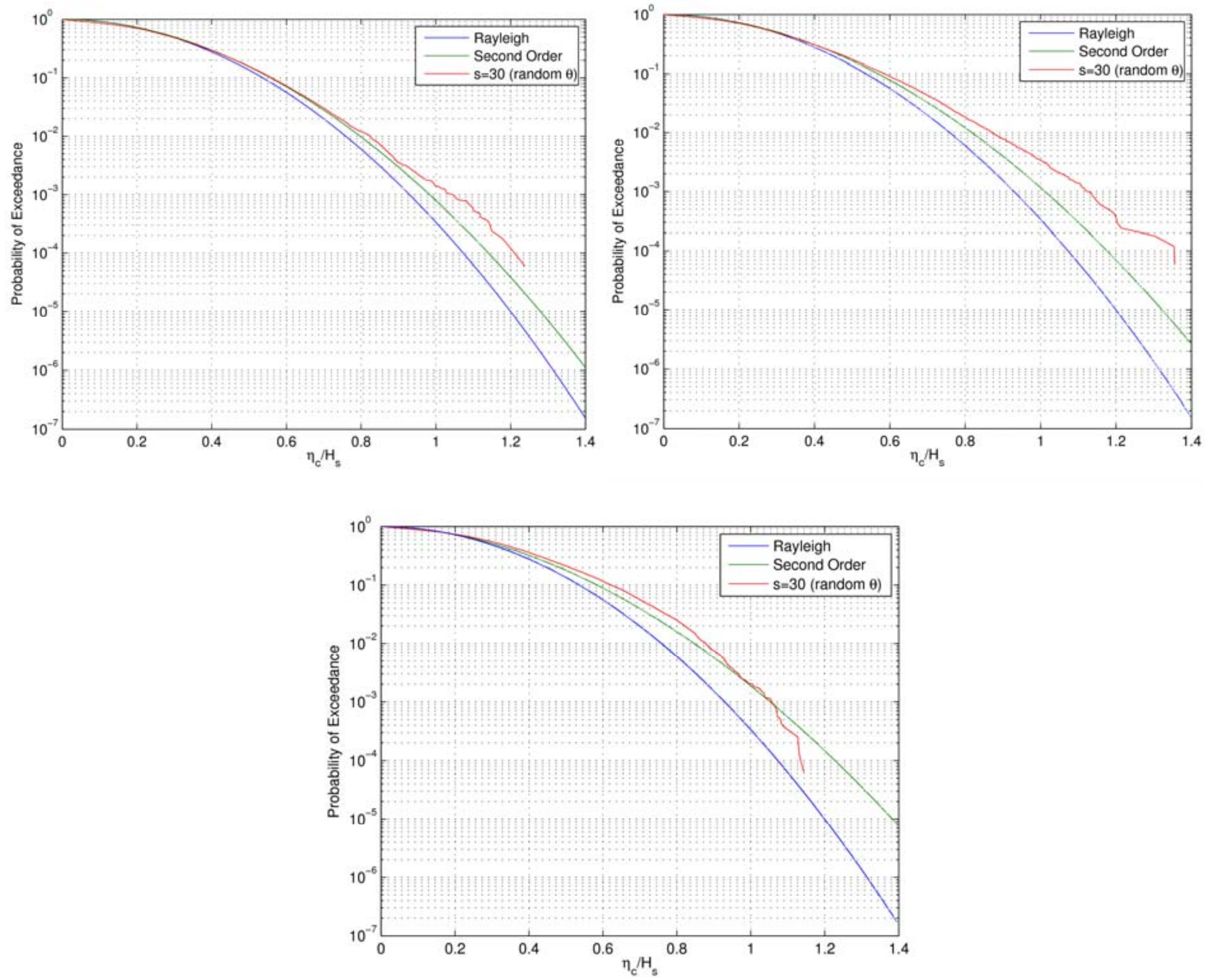

Figure 19. Crest distribution in the Imperial College basin for short-crested seas for T_p=16s (γ=2.5, s=30) and three different steepness values of H_s=10m (S1=3.7%) and H_s=15m (S1=5.6%) at top and H_s=20m (S1=7.5%) below, from [4]

From a steepness of 3.7% to 5.6% there is a clear increase of the tail of the distribution as expected. However, for the highest steepness of 7.5% this trend is not continued. On the contrary: at the lower probabilities the distribution curves downwards (even below second order). From observations in the basin it was concluded that this was due to wave breaking. So the increasing non-linearities due to the higher steepness are counteracted again, as we have seen for the long-crested waves, by wave breaking. This is an issue that certainly requires further research, as the present results are for one (limited) spreading (s=30) and one peak enhancement factor (γ=2.5) only. The results also apply for a condition relatively close to the wave generator (within one wave length), whereas they can develop further over distance (although breaking will still play a limiting role), as was seen in Figures 9, 10 and 11 for long crested waves.

The growth of wave crests over time and distance through resonant interactions is very dependent on the local steepness and time the different wave components can interact. In short crested waves the growth is less than in long crested waves, in which all components are travelling in the same direction. This would explain why the growth of the extreme wave crests over distance is slower in short-crested waves than in long-crested waves, as can be seen from the limited growth between two positions in the Offshore Basin shown in Figure 20.

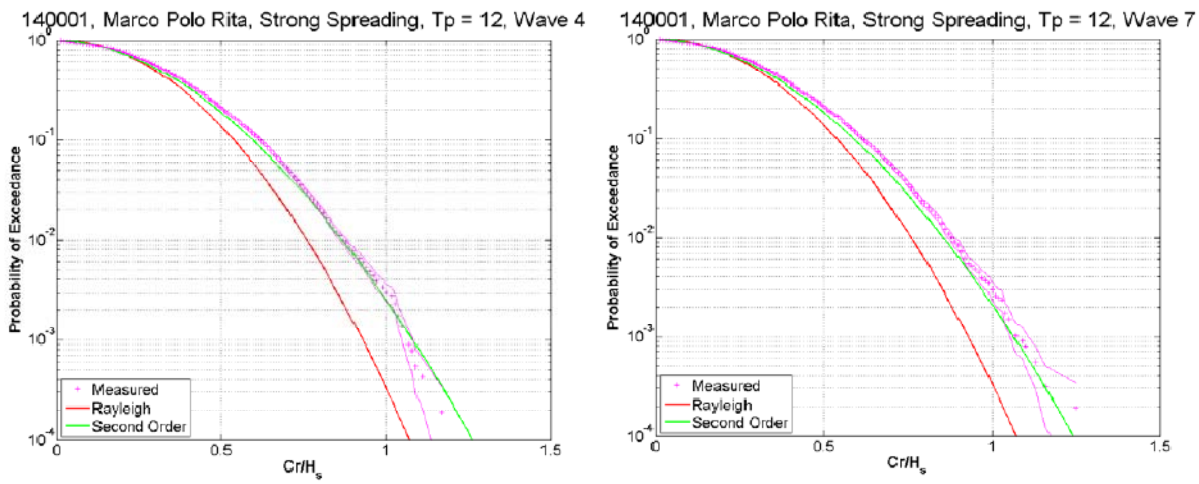

Figure 20. Comparison of crest height distributions at two distances (649m for WAVE4 and 1198m for WAVE7) from the wave generator in short-crested seas (s=4, from [3]), S1=7.5%

Still there seems to be an increase above second order in this case, which also seems to be dependent on the spreading. The case with low spreading (s=15) in Figure 21 shows a larger deviation:

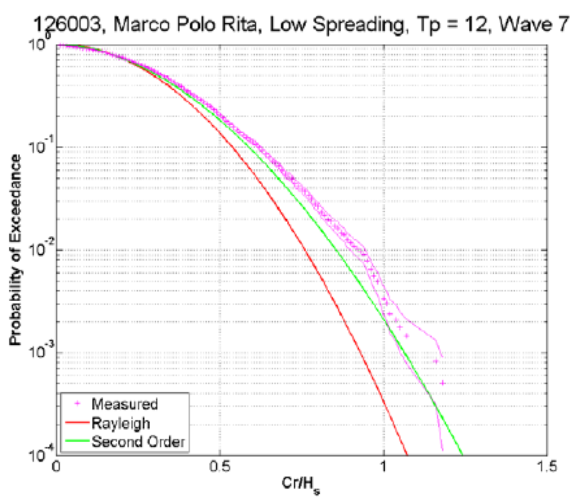

Figure 21. Crest height distribution in the MARIN Offshore Basin for a case with low spreading (s=15, from [3]) at 1198m from wave generator, S1=7.5%

This seems to imply that within short-crested sea states individual long crested wave groups can occur in which non-linear resonant interaction would allow the waves to grow. We plan to investigate this possibility in future work.

So far individual sea states have been investigated. To look to more general trends, all the short crested waves available from the Offshore Basin (>100 hours full scale) were combined and plotted in Figures 22 (basin waves with strong spreading) and 23 (basin waves with low spreading).

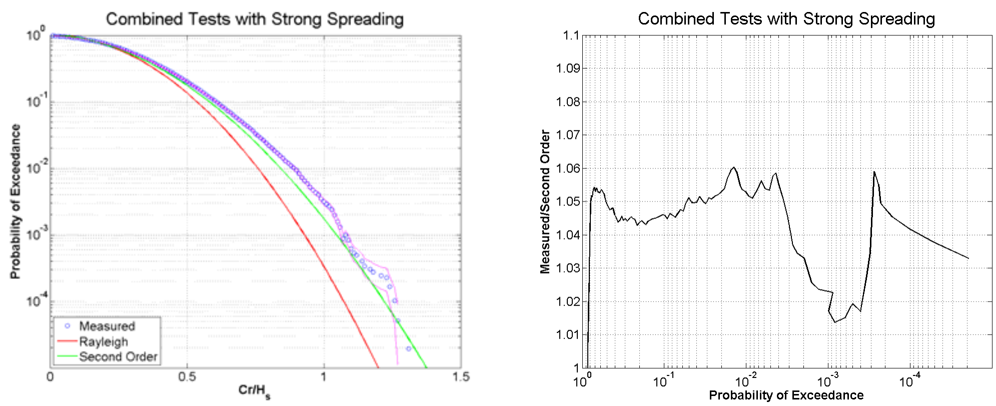

Figure 22. Crest distribution (left) and deviation from second order distribution (right) for basin waves with strong spreading (s=4 and 2D spectra with frequency dependent spreading).

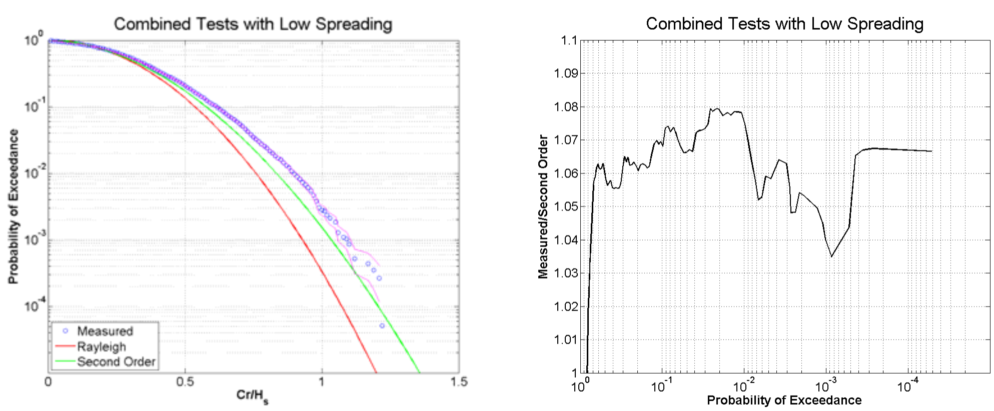

Figure 23. Crest distribution (left) and deviation from second order distribution (right) for basin waves with low spreading (s=15).

It is clear that the measured distribution is above the second order distribution, except in the extremity of the tail. This is quantified in the right hand figures, which divide the measured distribution by the second order distribution. The basin crests for spectra with strong spreading (s=4) are 2-6% higher than second order, with low spreading (s=15) they are 4-8% higher than second order. It should be noted that this difference is significantly smaller than the difference between second order and linear theory (Rayleigh), which is 10-15%. On the other hand it should be noted that the investigated sea state steepness values are limited: only up to around S1=7.5%.

Field measurements

Only a few of the field measurements studied included information on directional spreading, but the Oceanweather hindcasts [1] indicate that all of the storm sea states have directionally spread spectra. So it is assumed that all of the waves in the field measurements studied are short-crested.

One of the questions discussed in the analysis of the field data [2], was whether the occurrence of extremes in field measurements (typically 20 minutes intervals), was not just a matter of statistics: if a high wave occurs in such an interval, it directly shows up in the distribution as a large deviation from second order. Fortunately, for an installation in the North Sea a long duration measurement was available in the same sea state. Figure 24 shows increasing sample lengths of 20, 40, 60, 120, 180 and 360 minutes. Quantitatively, the freak wave height decreased from 27.5% to 13% larger than the Forristall (1978) distribution as the sample length went from 20 to 360 minutes. Similarly, the freak crest height reduced from 66% to 43% larger than the Forristall (2000) predicted value as the sample length increased from 20 to 360 minutes. In conclusion the sample length (at least for the example in question) does not explain the departure from Forristall statistics. It appears that at all sample lengths the design crest distribution has more scope for improvement than that of the wave height. Thus, there is evidence of effects above second order in the field data.

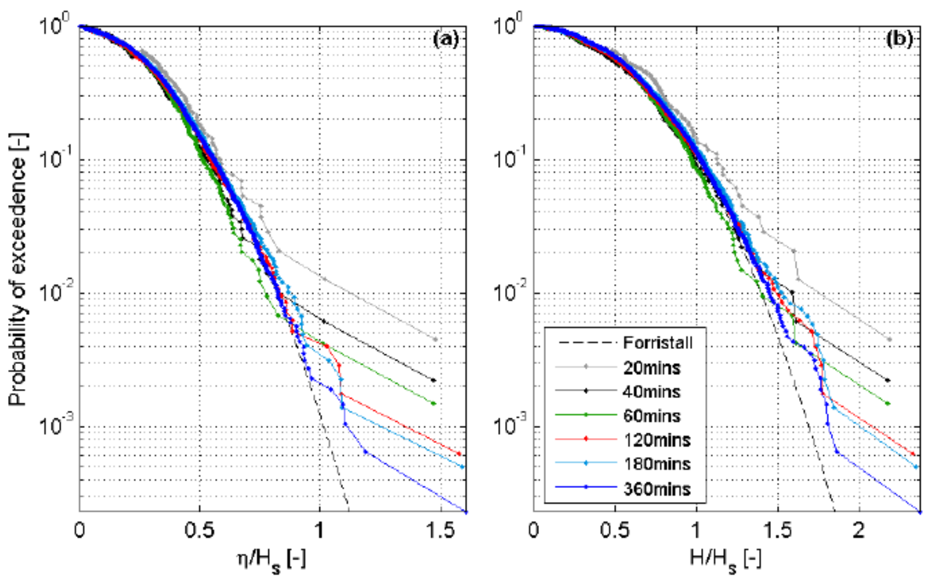

Figure 24. Effect of increasing the sample length on crest and wave height distributions (from [2])

This was investigated further based on the complete data base that was analyzed in the Crest JIP. Marios Christou and Kevin Ewans [2] first did extensive QC checks on the received data set of waves, resulting in a total reliable data base of 532,124 samples of 20-minutes (more than 177,000 hours). The probability distributions of the wave and crest heights were then compared to the Rayleigh and Forristall distributions for wave height and second order crest height.

Figure 25 shows that, when all the waves in the data base are used, the bulk of the waves obeyed the two Forristall distributions until η/Hs=1.25, which coincides with the freak wave criteria applied. After this point there is a discontinuity in the measured distributions.

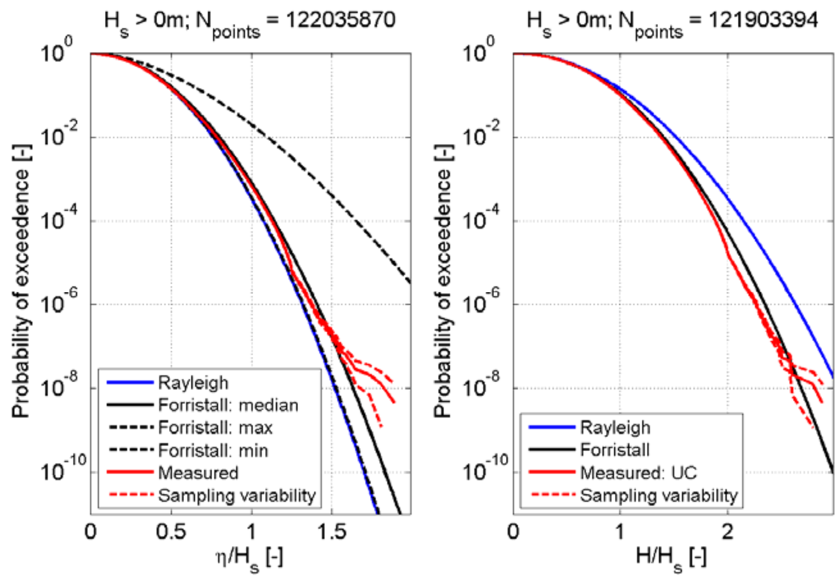

Figure 25. Crest and wave height distributions from field measurements (from [2]), full data base

The discontinuity in the measured distribution around η/Hs=1.25 could be a result of a number of factors. First, it could indicate that the normal and freak waves are parts of different statistical populations, and therefore, follow different probability distributions. Second, there could be a bias introduced during the QC procedure, as the freak waves have also been visually checked, whereas the normal waves only needed to pass the automatic QC checks. Finally, it is possible that the sampling rates of the field measurements (2Hz and 1Hz) are too low, especially for the shorter smaller waves, which might result in underestimation of higher wave heights and crests in these cases (this will be discussed in more detail later). In that respect it should be noted that 71% of the waves in the data base have an Hs between 0 and 2 m, with the related short wave length. If the smaller waves are removed, a much smoother distribution develops, as can be seen in Figure 26.

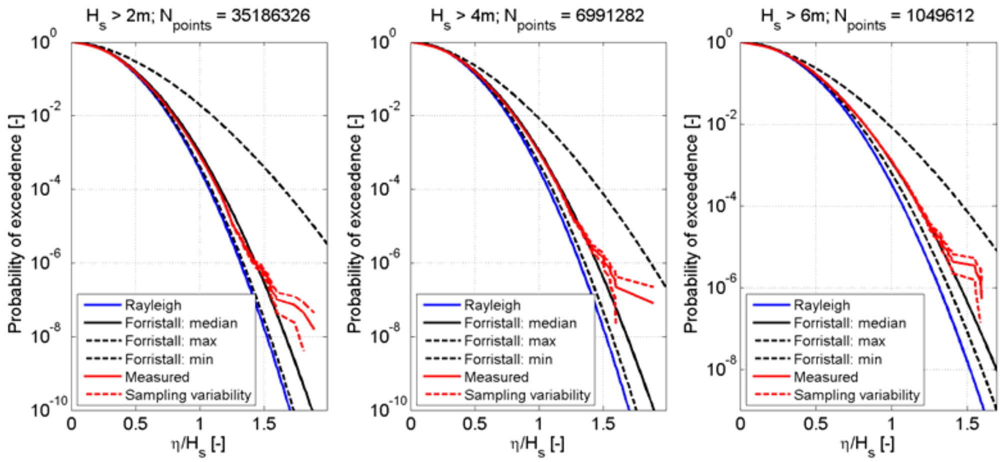

Figure 26. Crest height distributions from field measurements (from [2]), for Hs>2m, Hs>4m and Hs>6m (from left to right)

Something similar happens to the wave height distribution, as can be see in Figure 27 for Hs>6m. Except for the very tail, both Forristall distributions seems to be followed quite well for this data set. This still represents more than 1500 hours of high quality wave data, now more focussed on storm conditions.

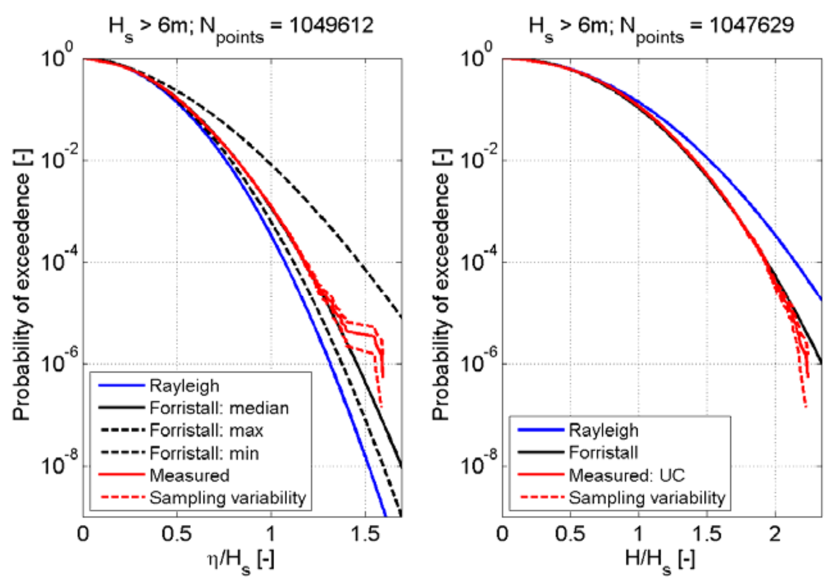

Figure 27. Crest height and wave height distributions from field measurements (from [2]), for Hs>6m

It should be noted that this data set includes sea states with a wide range of wave steepness, whereas the non-linearity develops with the wave steepness. This can also be seen in the expression for the 2nd order Forristall crest height distribution (Forristall, 2000):

$$S_1 = \frac{2\pi}{g}\frac{H_s}{T_1^2}$$

$$P(\eta) = \exp\left[-\left(\frac{\eta}{\alpha H_s}\right)^{\beta}\right] \qquad \alpha = \sqrt{1/8} + 0.2568 S_1 + 0.0800 Ur \qquad \beta = 2 - 1.7912 S_1 - 0.5302 Ur + 0.2824 Ur^2$$

$$Ur = \frac{H_s}{k_1^2 d^3}$$

The sea state steepness (S1) is an important parameter in this distribution. To investigate the effect of the sea state steepness on the measured distributions in the field, the data base was further divided in certain steepness intervals: 0-5%, 5-7%, 7-10% and 10-20%. They are shown in Figure 28.

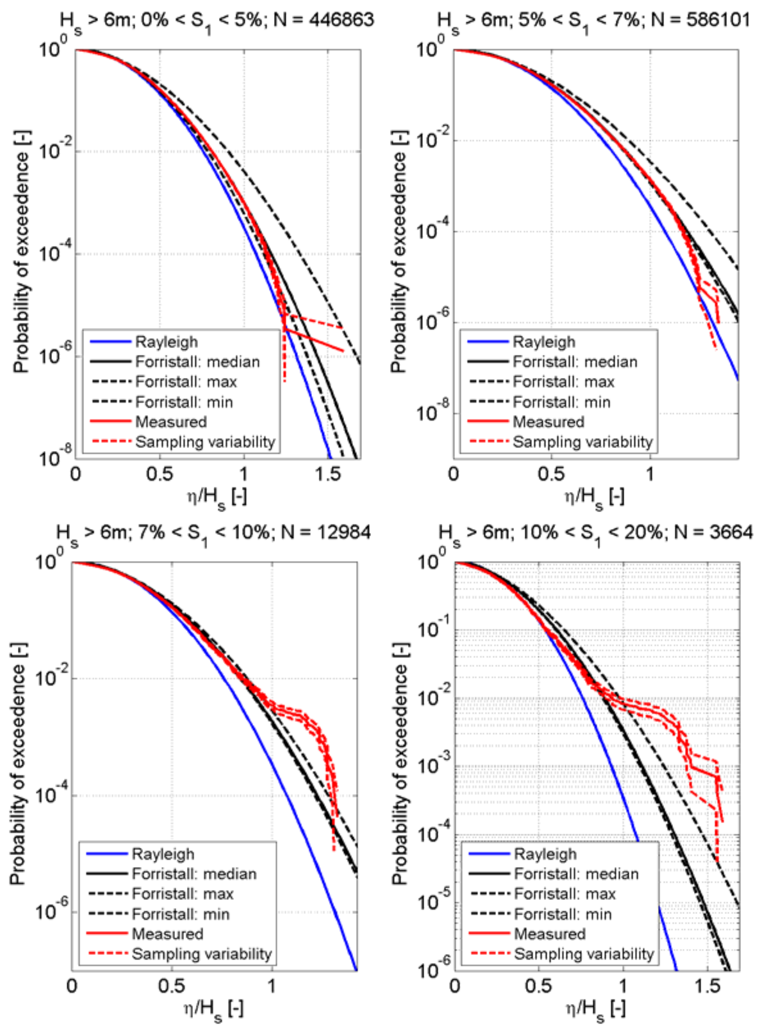

Figure 28. Crest height distributions from field measurements, for Hs>6m with different seastate steepness (S1) levels: 0-5%, 5-7%, 7-10% and 10-20%

The following observations can be made:

- Between 0 and 7% sea state steepness the measured distribution follows the second order distribution quite well, except at the tail where it drops below the second order line.

- Above 7% (and particularly above 10%) sea state steepness the higher extremes in the distribution deviate strongly from second order. In these sea states the non-linearities seem to be strong enough for a larger time and space to develop higher extremes.
- Even the distributions for the steepest sea states seem to be limited in crest height (and deviation from second order). Similar to what has been observed in the basin tests (Figure 15, 16, 19) an initial growing departure from second order is stopped by the physics of the waves. The most probable cause for this limitation is the wave breaking. This is in continuous competition with the non-linearities that make the wave grow.

One should realize that Figure 28 shows conditional probabilities: $P(\zeta>a|H_s>b \ \& \ c\%<S1<d\%)$. The probability of the higher sea state steepness values themselves, such as 10%<S1<20%, are low. So the total probabilities at the tail of the distributions in Figure 28 are extremely low.

Conclusion and Future work

Based on the presented results for long and short-crested numerical, field and basin results, it can be concluded that the statistics of long-crested waves are different than those of short-crested waves. But also short-crested waves show a trend to reach crest heights above second order. This is in line with visual observations of the physics involved: crests are sharper than predicted by second order, waves are asymmetric (fronts are steeper) and waves are breaking.

The following future work is recommended:

1. The CresT project showed that accurate simulations of wave statistics and vessel responses must use directionally spread seas. For that to be done, good information about the directional spectrum in storm seas is needed. The spreading function for the simple case of fetch-limited seas has been well-established, but storm seas, and in particular hurricane seas can be much more complicated. An investigation of wave measurements and hindcasts should be undertaken to establish guidelines for directional spectral shapes.

2. Long-crested waves are necessary for third-order interactions to modulate the spectrum and produce high crests. Natural waves are generally short-crested, but a very long crest could arise by chance in a natural sea state. Forristall made long linear simulations for fetch-limited spreading and found visually long crests such as shown in Figure 29. The initial conditions that lead to these long crests should be used as input to a non-linear simulation to see if they result in abnormally high crests. Also the sensitivity for the spreading should be considered in this respect, as well as non-linear processes that might create local long-crested events in which extreme events can occur.

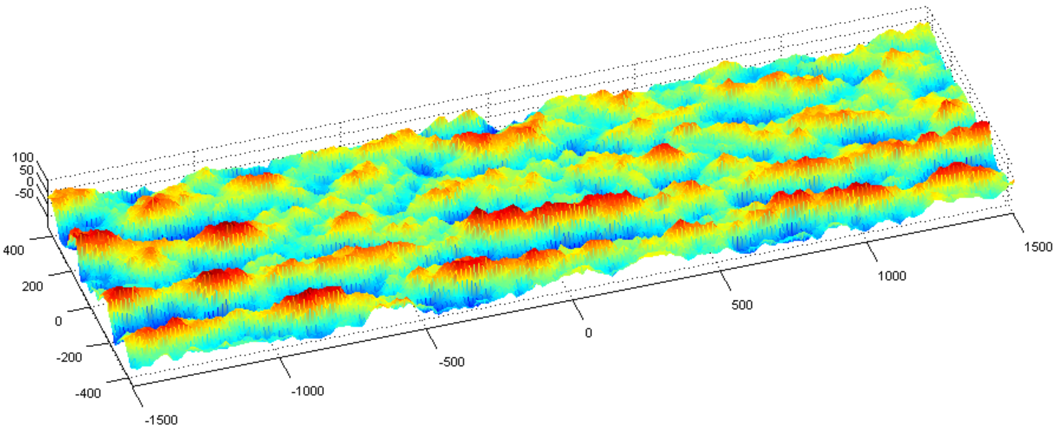

Figure 29. Long crests produced from a linear simulation

3. The high frequency tail of the crest distribution and wave spectrum in short-crested waves needs to be investigated further in relation with the effects of third-order interactions, steep fronted waves, wave breaking and wind forcing.

4. Wave breaking in deep water needs to be investigated because of its effect on wave kinematics, as shown in Figure 30 (from [4]):

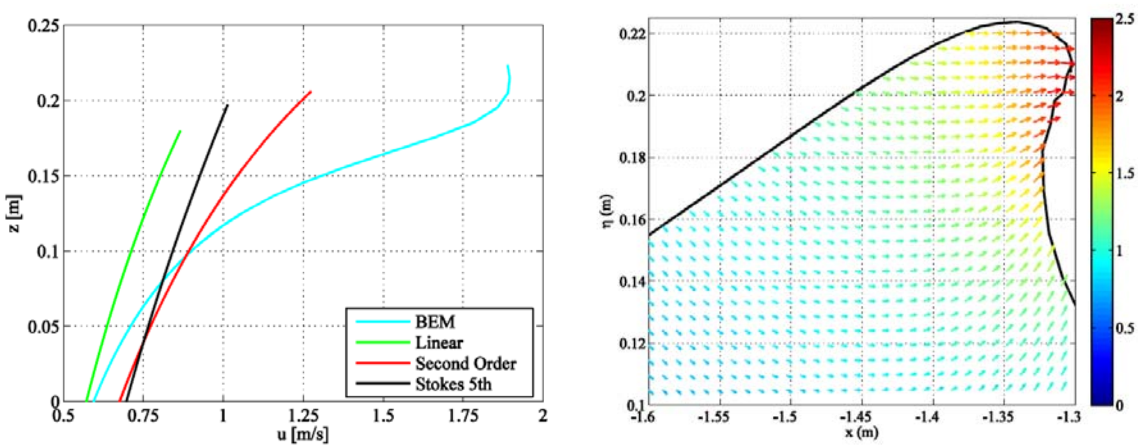

Figure 30. The left panel shows predictions of horizontal velocities under the crest of a wave predicted by various theories. The right panel shows the very high velocities predicted in a breaking wave (from [4])

5. The effect of short-crestedness on extreme wave loading and response needs further investigation, as indicated in the loads on the TLP in long and shortcrested waves below (from [6])

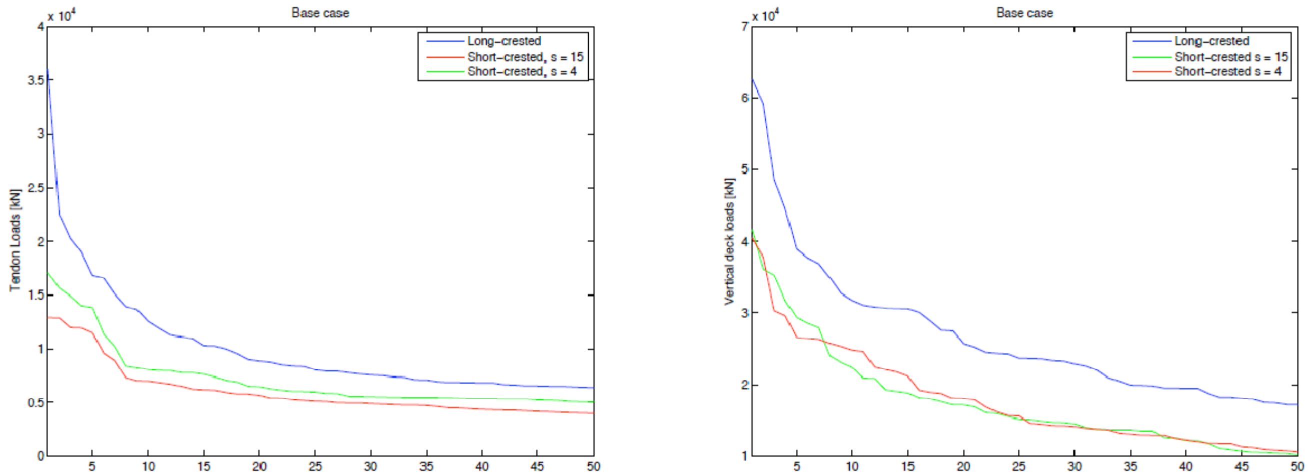

Figure 31. Extreme loads (tendon loads left, deck load right) as a result of wave directionality: long crested waves (blue), short crested waves s=4 (red) and short crested waves s=15 (green). The horizontal axis gives the highest 50 events recorded from the highest (1) to the lowest (50). Figure taken from [6]

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CresT JIP:

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2. *Work package 2, 'Analysis of field data' by Shell*
3. *Work Package 2, 'Offshore basin wave statistics' by Forristall Ocean Engineering*
4. *Work package 3, 'Extreme waves: deterministic and probabilistic modeling' by Imperial College*
5. *Work Package 3, 'Extreme wave modeling: Probabilistic modelling of extreme wave crests' by Ocean Wave Engineering*
6. *Work Package 4, 'CresT JIP TLP model tests in extreme wave conditions' by MARIN*
7. *Work Package 5, CresT JIP reliability analysis of TLP' by DNV*

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