Freak Waves: A Suggested Definition and Possible Consequences for Marine Structures

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Abstract. Target annual exceedance probabilities of design loads of offshore structures on the Norwegian Continental shelf are briefly discussed. It is proposed to define freak wave events as events that are well beyond what is typically expected within wave theories utilized for structural design. With this background, the question of whether or not freak waves are of concern for practical design work is discussed. The discussion is not conclusive, and major focus is given to some questions that need to be properly answered before a final conclusion can be made.

1 Introduction

This paper is prepared as an introductory lecture to a session discussing rogue waves and practical problems related to their possible existence. The paper do not present any new evidences of freak waves. The purpose is merely to present some few questions that need to be properly answered before it can be concluded whether or not freak waves represent a threat to structural integrity. Hopefully, these questions and accompanied discussions can act stimulating on those research groups addressing freak waves from a more basic research point of view.

Offshore structures at the Norwegian Continental Shelf are with respect to overload designed against environmental loads corresponding to an annual exceedance probability of 10^{-2} multiplyed by a partial load factor of 1.3, Norsok(1999). Provided that the load versus exceedance probability is of a well behaved nature, the design load thus obtained is tacitly assumed to result in a reasonable platform safety against collapse. However, this may not be the case if for some reason the load – exceedance probability relation changes abruptly in a worsening direction for exceedance probabilities between 10^{-2} and 10^{-4}. Such an abrupt change in load pattern could take place if the most extreme waves impact the deck structure. An illustration of the load – exceedance probability relation for a well behaving and a bad behaving response problem is shown in Fig. 1.

In order to ensure that an ill behaving response problem is not slipping unnoticed through the design process, Norwegian Offshore Regulations, NPD(2001), also requires that the structures shall withstand 10^{-4}-probability[1] environmental loads with at most some local damage. There is not a one-to-one relation between wave crest height and platform loading, but in most cases there is a rather large positive correlation. This means that if we shall be able to predict reasonable estimates for the q-probability loads, $q=10^{-2}$ and 10^{-4}, the wave models used for design should accurately reflect wave events with occurrence probabilities of the order of magnitudes.

Accordingly, a quantity of crucial concern is the very upper tail of the annual distribution function of wave events and loads, i.e. annual exceedance probabilities in the range 10^{-2} – 10^{-5}. Provided that the sea surface can be modeled as a stationary and homogeneous second order random field, see e.g. Marthinsen and Winterstein (1992), Forristall (2000), it is expected that it is possible to estimate the upper tail of the annual extreme value distributions with a sufficient accuracy. The challenging question, however, is whether or not there exists wave phenomena beyond our adopted design model which may affect the very upper tails significantly.

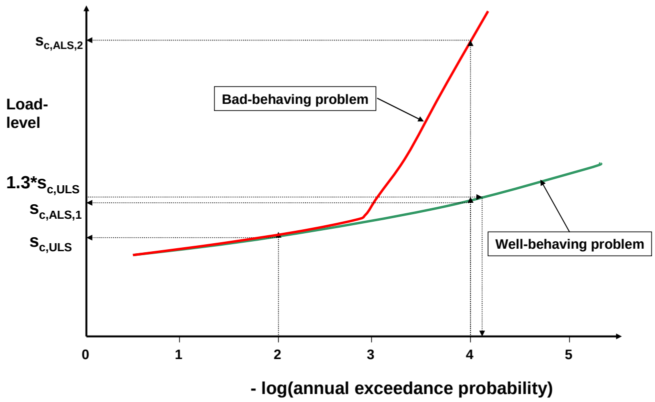

Fig. 1. Illustration of well-behaving and bad-behaving response problem.

2 Are rogue waves a problem for structural design?

The answer to this question depends very much on what is meant by a rogue wave. There is at least two options: i) “Classical” extreme waves and ii) Freak extreme waves. Unfortunately, it is not always clear what people mean when they refer to rogues waves. As an extended introduction, some paragraphs will therefore be spend on clarifying what will be meant throughout this paper.

[1] Q-probability event means an event corresponding to an annual exceedance probability of q.

"Classical" extreme waves

By classical extreme waves, we will herein think of rare members of a population of wave events defined by modeling the surface process as a piecewise stationary and homogeneous slightly non-Gaussian random field. The word "classical" is introduced since this approach is what in principle is available for routine design. Over the years, the so-called "classical" population has evolved somewhat. One to two decades ago, the surface process was often modeled as Gaussian random field. As a consequence of that the "classical" extreme crest height population of those days was shifted slightly to smaller values than those being in agreement with the present definition.

This type of extreme waves are in most cases properly accounted for by the offshore industry, provided some 10^{-4} – probability wave load scenario is implemented. Traditional shipping may have some room for improvements both when it comes to the implementation of a slightly non-Gaussian surface process and the adopted exceedance probabilities for the design loads. The latter is in particular the case when it comes to slamming and green water related problems.

It is important to realize that even within "classical" extreme waves population, wave events which may represent a threat to the integrity of a structure do exist. However, their annual exceedance probability for a given site should be lower than say 10^{-5} if a structure is properly designed.

Freak (extreme) waves

Herein we will define freak waves as typical members of population being defined by physical mechanisms well beyond those underlying *"classical" extreme waves.*

These types of extreme wave events are not explicitly accounted for in the design process. If such a population exists, it may challenge present design recipes if it significantly affects wave properties (crest heights, wave heights, wave steepness) at a given site corresponding to annual exceedance probabilities of 10^{-3} – 10^{-5} . It should be noted that we throughout this paper always will refer to the annual extreme value distribution functions at a given site. This because a structure can not simultaneously sample wave events more than at one site. The rule requirements to target maximum exceedance probability of the design loads, therefore refer to annual exceedance probabilities at a particular site. In case of traditional shipping, this site would be a site moving along a given route.

Which out of these populations is the most common adopted definition of rogue waves is hard to say. It seems as if the rogue waves population often is meant to capture both populations referred to above. From a practical point of view that is not convenient, because a major part of the rogue wave population, *"classical" extreme waves*, does not represent a problem, while the *freak extreme waves* population, if it exists, may represent a challenge.

3 Suggested definition of freak waves

The most common definition of a freak wave, is to define a wave as a freak wave if the wave height to significant wave height ratio or the crest height to significant wave height ratio exceed some thresholds. A factor definition may be useful as a first indicator of possible freak event. In this connection, the recommended thresholds should account for the duration of the observation window, i.e. is the observed maximum a 20-min. maximum, is it a 3-hour maximum or is it a storm maximum.

From a practical point of view it seems more convenient to anchor the definition of a freak wave to mechanisms not captured by the wave models used for design purposes. It is therefore recommended to define freak waves as follows, Haver (2000):

A freak wave event is an event (crest height, wave height, steepness or group of waves) that represent an outlier when seen in view of the population of events generated by a piecewise stationary and homogeneous second order model of the surface process.

The definition is related to major deviations from a second order model because this is the most sophisticated model that is available for routine design work. As more sophisticated model for design is developed, the *"classical" extreme wave* population will grow on the cost of the *freak wave population*.

If one is to look for freak waves in available measurements, one will need a freak wave indicator as the observations are scanned. For such a purpose a factor threshold is useful. If we are basing the data search on scanning of 20-min. time series, one should establish proper threshold for this experiment. If the sea surface is modeled as a second order process, the 99-percentile of the ratios $c_{20-\min.}/h_s$ and $h_{20-\min.}/h_s$ read about 1.25 and 2.00, respectively, Haver(2000). If an observation exceeds this threshold, one may at a significance level of 1% reject this observation as a realization from a second order process of 20-min. duration. However, further investigations should be carried out before the event is concluded as belonging to the *freak extreme waves* population.

If the observation window is increased to 3-hours, more adequate thresholds would be 1.50 and 2.45, respectively. If a storm is defining the observation window, 1.60 and 2.55 will probably represent adequate thresholds if a 1% significance level is found proper for the freak wave indicator.

The advantage of this definition is that we accept that rather lather freak wave indicator factors occur even within the "classical" extreme waves population. If a separate phenomenon can be excluded, freak wave should be of no concern. If a structure is being hit by an unexpectedly large wave event, it is then merely a matter of being at the wrong place at the wrong time. The annual occurrence probability of this event, however, should be well below the target annual exceedance probabilities of the design loads.

Finally, it should be pointed out that the thresholds recommended above, refer to observations from a given site. If the observation window is extended to also cover spatial domain, the thresholds for the indicator should be significantly increased in order to account for effects discussed by Krogstad et al. (2004).

4 Why should we be concerned about freak waves?

It is seen from Fig. 1 that an ill-behaving response problem being overlooked in the design process could represent a threat to the structural integrity. The figure reflects the airgap problem. In practice this problem is dealt with by requiring that the airgap is sufficiently large for the annual wave-deck impact probability to be less than 10^{-4}.In this connection, the 10^{-4} crest height is estimated using the classical extreme wave population. If a freak wave population exists and if it is realized sufficiently frequent to effect the interesting part of the annual extreme value distribution of the crest height, freak waves may represent a source for an ill-behaving response problem, i.e. a scenario where for a low exceedance probability the load increases abruptly. This is because a fatter tail will make a wave-deck impact more probable. The possible effect of freak waves which we should be concerned about is illustrated in Fig. 2.

If a freak wave population exists, what is the problem? For ships and offshore platforms, a freak wave will mainly represent a problem if its crest hits structural members which is not designed for wave loads. As far as no new members are exposed, the global loading due to a freak wave is most probably smaller than the global loading in connection with a “classical” extreme wave. However, it is recommended that further work are carried out in order to establish some documented knowledge on the freak wave kinematics.

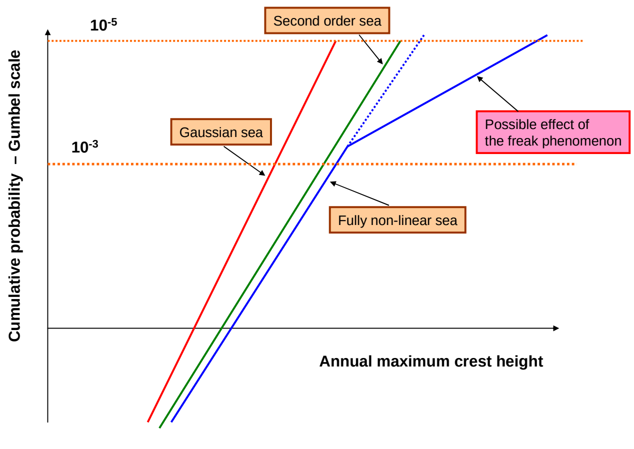

Fig. 2. Possible effect of freak waves of annual extreme value distribution of wave crest height

5 The freak wave challenge

With respect to waves, offshore structures are designed against the q-probability waves from the population referred to herein as the "classical" extreme waves. If the design process also involves a proper check of the structure against accidental waves (10^{-4} – probability waves), a certain robustness against freak wave events is achieved. This is under the assumption that it is not the group involving the worst waves from the "classical" extreme waves that is focused into a single majestic wave. However, if this assumption is not true, freak waves may, if they exist as a separate phenomenon, represent an unknown or unquantified threat to marine structures. At present it is not possible to approach freak waves in a rational way in the design process.

In order to be able to account for possible freak waves in rational design recipe, the following questions need to be answered:

- *Does a separate freak wave population exist?*
  One needs to identify the underlying physical mechanisms that can make a freak wave development possible.
- *Given a separate population exists, what is the conditional probability, say per 3-hour duration of a sea state, for a freak wave development given some engineering sea state characteristics?*
  From a design point of view, a freak wave does not represent a problem unless it at a given site occurs sufficiently frequent to effect our predictions of 10^{-2} - and 10^{-4} – probability wave events.
- *Given a freak wave occurs in a 3-hour sea state with given characteristics, what is the conditional distribution for the freak wave amplification factor?*
  The freak wave amplification factor is defined as the ratio $c_{3hr,freak} / c_{3h,nonfreak}$. In some cases a freak wave will not be larger than the largest wave in another group of the sea state not being exposed to a freak wave development. On the other hand, if it is the largest group of the sea states that developes into a single majestic wave, the amplification factor may be considerable.

Wave data collection programs will possibly not be the most adequate approach for concluding on the existence of a separate freak wave population. In case of an unexpectedly large observation, one will face the following question, Haver and Andersen (2000): Is the observed wave a very rare realization from the typical slightly non-Gaussian sea surface population, or, is it a typical realization of a very rare and strongly non-Gaussian sea surface population? A more fruitful approach in the long run is to develop mathematical models accounting properly for the underlying physics including the physics that may govern a freak wave development. If such a model becomes available, one should in principle be able to answer the two last equations through time domain simulations of sea surface fields.

A rather qualitative assessment of whether or not freak waves represent a problem for practical design was presented by Haver et al. (2004). The basic idea of that assessment is that we for any sea state can establish a proper extreme value distribution for $C_{3hr,nonfreak}$, i.e. the 3-hour maximum crest height given no freak wave development took place. The conditional probability of freak wave development is measured by a two outcome variable, K. If no freak wave development take place, K=0, while K=1 describes a freak wave development. At present we do not know the conditional probability of K=1 for the various sea states and in the paper it is simply modeled as a bell shape function of h_s and t_p. An example of $P(K=1 \mid H_s, T_p)$ is shown in Fig. 3. In the study some sensitivity studies of the parameters of this function are included.

The 3-hour maximum accounting for a possible freak wave development is written on the following form:

$$C_{3hr,freak} = C_{3hr,\ nonfreak} + K^{*}\Delta C_{3h,freak} = C_{3hr,\ nonfreak}(1 + K^{*}\Lambda) \quad \textbf{(1)}$$

$\Delta C_{3h,freak}$ is the increase of the 3-hour maximum crest height due to the freak wave development. Λ describes the same quantity normalized by the 3-hour maximum if no freak wave development takes place. $\Lambda = 0$ if the freak wave crest height is not the highest crest height of the sea state. This is more or less arbitrarily assumed to be the case in 25% of the cases with a freak wave development. The distribution function for Λ is shown in Fig. 4. The qualitative study indicates that if the chance of a freak wave development is very small, which is what available observations suggest, freak waves will not affect design wave events. However, one has to keep in mind that most of our observations correspond to sea states not much more severe than what the 1- to 10-year contour lines shown in Fig. 5 suggest. However, a wave event is not expected to be critical regarding structural integrity before we approach or exceed the 10000-contour of Fig. 5.

If the conditional probability of K=1 is much higher for sea states beyond what are presently observed, freak waves may represent a threat to marine structures. It is therefore recommended that research is continued until it can with reasonable confidence conclude that the freak wave probability is not positively correlated with sea state severity. Severity is in this connection not measured only in significant wave height.

6 Possible mechanisms for a freak wave development

Herein we will not review the various mechanisms that have been proposed as possible freak wave mechanisms. The reader could review other presentations at this workshop or consult proceedings from the previous rogue waves work shop, Olagnon and Athanassoulis (2001). One of the mechanisms, Benjamin-Feir instability, seems to require that surface process need to be rather narrow banded both frequency (wave number) and direction in order to be realized. The real ocean surface is typically short crested suggesting that the real sea surface is less exposed to the self focusing of major wave groups. However, the real ocean is not homogeneous and stationary to the extent that is typically utilized in ocean engineering. Fig. 6 shows an illustration of a sea surface that is generally of a short crested nature, but where a sub-area is assumed to exist. Is this a possible scenario in the real world? Are we smoothing away these possibilities by our input assumption of piecewise homogenity and stationarity? One should probably approach these questions rather open minded although if these assumptions have to be skipped, the ergodicity assumption that is underlying much of our work in ocean engineering can be questioned.

Satellite observations of larger areas may prove very useful when it comes to verify our assumption of sea surface homogeneity.

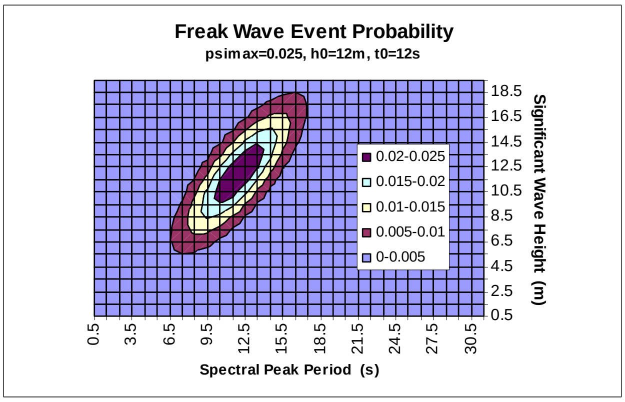

Fig. 3. Illustrative conditional probability of freak wave phenomenon given sea state characteristics.

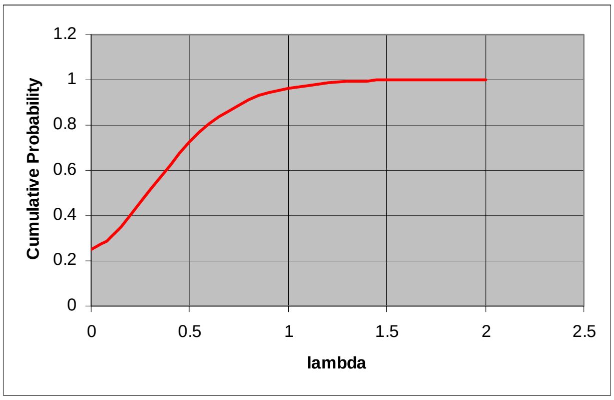

Fig. 4. Illustrative conditional distribution function of the freak wave development factor.

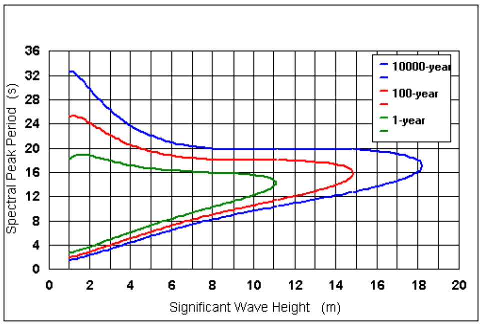

Fig. 5. q-probability contour lines for H_s and T_p for a Northern North Sea location

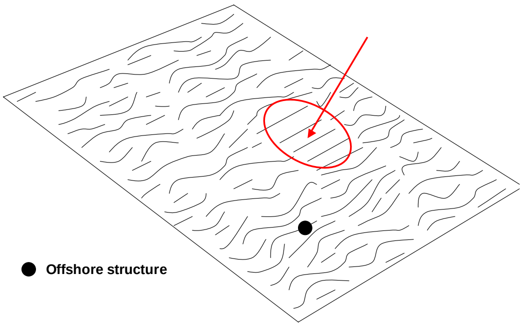

Fig. 6. Illustration of a short crested sea surface with a long crested sub-domain.

7 Conclusions

The discussions presented previously can be summarized as follows:

- Freak waves should be defined as a separate population well beyond the population used for design purposes.
- Freak waves are not likely to represent a problem for offshore structures if their frequency of occurrence experienced for the sea states observed so far is generally valid.
- There is some concern that traditional ships may experience considerable damages in extreme wave conditions, even if the waves are well within the classical extreme wave population.
- Freak waves may be of some concern if their conditional occurrence probability is increasing as we enter into the range of non-observed sea state severities.

- A first step to gain some robustness against unknown freak wave extremes, could be to involve an accidental wave event (10^{-4} – probability wave event) into the design process.

8 Acknowledgement

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