**Proceedings of the ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering**
**OMAE2016**
**June 19-24, , Busan, South Korea**

**OMAE2016-55091**

# STATISTICAL INVESTIGATION OF THE SURFACE PROFILE OF ROGUE WAVES IN 2D NON-BREAKING SEAS

**Qiuchen Guo**
Department of Mechanical Engineering
University of California Berkeley
Berkeley, California 94720
Email: qiuchen@berkeley.edu

**Mohammad-Reza Alam**
Department of Mechanical Engineering
University of California Berkeley
Berkeley, California 94720
Email: reza.alam@berkeley.edu

## ABSTRACT

*Rogue waves or freak waves are very large amplitude waves compare to the ambient waves in a given sea state. There are very few recording of such waves and therefore, despite years of research, very little is known about their properties. Here we invoke a statistical approach to find out about the typical shape of these giant waves. We consider different sea states and unidirectional vs crossing seas and study how each environment affects the morphology of oceanic rogue waves.*

## INTRODUCTION

Oceanic rogue waves, whose heights unexpectedly exceed the typical height of the background sea state, reported to have caused serious damages to the offshore structures and ships over the past decades. Mallory [1] analysed 12 extreme wave events in the south of Africa where the giant waves are enhanced by the Agulhas current with some caused considerable damages to vessels. Several other accidents are summarized by Toffoli *et al.* [2], Faulkner [3], Ersdal [4] and Pelinovsky & Kharif [5]. Although the reported observations of rogue waves are traced back to long time ago, the first actual measurement of the rogue was obtained on Jan. 1st 1995 [6, 7], which is usually known as the *New Year Wave* or the *Draupner Wave*. The *New Year Wave* was measured near the Draupner platform during a relatively heavy winter storm and has been studied in details theoretically [8, 9], numerically [10] and experimentally [11, 12]. Another famous measured rogue wave is the one recorded in the Black Sea [13], which has a height 3.9 times as high as the background significant wave height. Besides the rogue waves that are measured by a floating buoy, the employment of the synthetic aperture radar (SAR) has opened a new door of possibilities for detecting rogue waves over large spatial and time domains [2, 14]. Although intensive studies have been carried out on the rogue wave, the statistical properties and actual shape of the rogue waves are still unclear mainly due to scarcity of a large database of the field measured rogue waves [15].

It is of great interests to know what an actual rogue wave looks like. The physical mechanisms behind the extreme waves have been intensively studies, however, remains not fully understood and identified [16,17]. By comparing the rogue waves from numerical simulations with the measured rogue waves in field or experiments, we can identify the suitability of the theoretical model and the numerical method to obtain rogue waves and potentially find out the physical mechanism behind the extreme waves [16, 18–20]. For example, by comparing the experimental waves generated using the Ma breather solution with the field measured *New Year Wave*, Clauss [21] revealed the suitability of using the Ma breather solutions to reproduce the rogue wave dynamics. It is also shown that the mechanism of modulational instability can also leads to extraodinary large waves in intermediate depth. Moreover, Faulkner [22] extensively assessed the loss of Derbyshire and suggests to revise the design code to consider the extreme waves. A correct knowledge of the rogue wave profile is potentially beneficial to the design of offshore structures and ships that would be located in the path of such waves.

The study of the identical wavelength and wave height of the rogue wave in a given sea state can have important implication in revising the design code to the offshore structures [23, 24].

The study on the rogue wave profile can be based on the few field measured rogue waves [9–11, 25–27], theoretical and numerical solution to (modified) nonlinear Schrödinger equation (NLSE) [9, 10, 10, 28, 29], or the numerical simulation that solve the fully nonlinear wave evolution equations [24, 30–33]. Most of the research on the rogue wave profile in the past is focused on the profile in time domain rather than that in spatial doman. Chabchoub [28] designed experiments in observing the time evolution of rogue waves governed by NLSE and compare the experimental results with the Peregrine solution. Taylor [26] detailed studied the time series of the *New Year Wave* and the background sea states, then use the 5th order New Wave, which is a model used in the offshore engineering, to reproduce the *New Year Wave*. Guedes Soares & Pascoal [27] assessed the suitability of using the New Wave to describe the rogue wave profile by comparing the field measured rogue wave data in the North Sea with the numerical results in time domain. In the mean time, only a few work has been conducted to study the properties of the rogue wave profile in spatial domain. This is mainly contributed by the fact that nearly all the hard evidences on rogue waves come from oil-platform measurements [17], which are fixed in space and hence record the time series of waves. On the other hand, it is also of significance to study the spatial characteristics of rogue waves. Xiao [33] used the proper orthogonal decomposition (POD) on the numerically generated rogue waves to obtain the identical rogue wave profile in space and find that the averaged rogue wave has a symmetric shape with respective to the peak. However, many of the field measured rogue waves do not have symmetric spatial profile respective to their peak. Although the *New Year Wave* shows symmetric shape in time domain [8], Clauss & Klein [12] showed that the *New Year Wave* is not symmetric in space by reproducing this rogue wave in the wave tank. Moreover, the rogue waves in the Gulf of Tehuantepec , reconstructed using the airborne spatio-temporal measurements, are also not always symmetric in space [34]. The numerical study by Gibson [32] also shows that the rogue wave obtained using the fully nonlinear simulation is not as symmetric in space as that obtained using the linear or weakly nonlinear model. All these observations lead to the significance of this paper to identify the more realistic rogue wave profile in space and time considering varying sea states.

It is known that the occurrence and probability of extreme waves do depend on the background wave fields, such as the sea severity, but the dependence of the rogue wave profile on the sea states needs to be identified. The World Meteorological Organization (WMO) sea state code classifies the sea state from 1 to 10 with increasing significant wave height $H_s$ and peak period $T_p$. It has been shown that the oceanic rogue waves are more likely to occur [35] with a larger height [36] as the sea state becomes rougher. In this paper, the rogue wave profile in different sea states will be identified.

Another important feature of the sea state is the travelling angle of the wave trains. The crossing sea state develops usually when the wind changes its direction and two or more wave trains are propagating at an oblique angle. Many of the accidents caused by rogue waves are reported in crossing sea states [37,38]. It is also suggested by Donelan and Magnussion [39] that crossing seas might lead to exceptionally high crests. Toffoli [40] stressed the modulation instability in crossing seas as a potential mechanism for the formation of rogue waves. To investigate the effect of the crossing sea state on the rogue wave profile, in the two dimensional framework, both unidirectional and crossing seas with two wave trains propagating in the opposite direction are considered in this paper.

Considering all the features of the sea states stated, we conducted large numerical experiments and obtain a large database with rogue waves for each given initial sea state characterized with the the Joint North Sea Wave Observation Project (JONSWAP) spectrum. The JONSWAP spectrum is proposed by Hasselmann [41] based on the measured data in the North Sea and has been widely used as the initial spectrum for the simulation of rogue waves [35,42–44]. Then we study the statistical properties of the rogue wave profiles with the stress on the asymmetric shape in spatial domain and more symmetric shape in time domain of the rogue wave with respective to its peak.

## PROBLEM FORMULATION

The surface wave dynamics, under the assumption of inviscid, irrotational, incompressible and homogeneous fluid, can be described by the potential flow theory. Here we solve the two-dimensional weakly nonlinear wave evolution equations in the Zakharov form [45] (see equation (1)), which can be solved through a phase resolved high-order spectral (HOS) method. Note that the governing equations are constructed in the Cartesian coordinate system located at the mean free surface with x as the horizontal axis and z as the vertical axis. The free surface elevation is denoted as $\eta$. The field velocity $\mathbf{u}(x,z,t)$ is expressed in terms of the velocity potential $\phi(x,z,t)$ with the relation $\nabla\phi = \mathbf{u}$. In terms of the velocity potential evaluated at the free surface $\phi^s(x,t) = \phi(x, z = \eta, t)$, the governing equations read

$$\eta_t = \phi_z^S(1+\eta_x^2) - \phi_x^S\eta_x \qquad \text{at } z = \eta(x,t) \qquad (1a)$$

$$\phi_t^S = -g\eta - 1/2(\phi_x^S)^2 - 1/2\phi_z^2(1+\eta_x^2) \qquad \text{at } z = \eta(x,t) \qquad (1b)$$

The phase resolved HOS method can take into account a large number of wave modes (typically $N \sim \mathscr{O}(1000)$) and high order of nonlinearity in wave steepness ($M \sim \mathscr{O}(10)$). The result converges exponentially fast with N and M up to wave steepness $ka \sim 0.35$ [46]. The ability of the HOS method in taking into account the high nonlinearity is crucial in analysing the properties of rogue waves since the rogue wave is known for its unusual large amplitude and thus high nonlinearity. Higher Order Spectral method was first formulated in 1987 ( [46,47]) to model nonlinear wave-wave interactions in deep water. It was then extended to the problems of wave-topography interactions in finite depth [48–50] and two-layer density stratified fluids [51–55] as well as wave viscoelastic-seabed interactions [56, 57]. The scheme has already undergone extensive convergence tests as well as validations against experimental and other numerical results [56,58–60].

In order to identify the statistical properties of the rogue wave profile, we conduct large number of numerical simulations and screen out $\mathscr{O}(100)$ rogue waves for a given sea state by detecting waves with $H_r > 2H_s$, where $H_r$ is the maximum peak to adjacent trough height of the rogue wave and $H_s$ is the significant wave height. The rogue waves are searched in different background sea states.

In reality, the initial surface elevation $\eta_i$ is obtained from the reconstructed wave field from the SAR images. However, to obtain a database with large number of rogue waves, we adopt the initial wave field characterized by the JONSWAP spectrum, which is defined by several sea state parameters. Sea state provides a general description of the sea roughness. In this paper, three sea states 4, 5 and 6 are considered, which represents the mild, rough and very rough sea state respectively. They have corresponding $H_s = 1.875$, 3.25 and 5 meter, and the peak period $T_p = 8.8$, 9.7 and 12.4 second. For a given sea state, the JONSWAP spectum can be calculated as in Equation (2) [61]:

$$S(\omega) = \frac{\alpha_p g^2}{\omega^5} exp(\beta)\gamma^\delta \tag{2}$$

Here, the constant $\alpha_p$ is related to the amplitude and energy content of the spectrum which is defined as $\alpha_p = H_s^2 \omega_p^4/(16 I_0(\gamma) g^2)$, where $I_n(r)$ is the n-th order moment of this spectrum, which can be computed numerically. The significant wave height $H_s$ is defined as the mean wave height (trough to crest) of the highest one third of the waves (i.e. $H_s = 4\sqrt{m_0}$, where $m_0$ is the zero-th order moment). The variable $\beta = -1.25(\omega_p/\omega)^4$, where $\omega_p$ being the peak radial frequency and $\omega$ being the wave radial frequency. The peak enhancement factor $\gamma$ varies from 1 to 9. The typical value of $\gamma$ is 3.3 and hence $I_0(3.3) = 0.3$. And $\sigma$ equals 0.07 and 0.09 respectively for $\omega \leq \omega_p$ and $\omega > \omega_p$. The power spectrum can be expressed in terms of wavenumber by using the relation $S(k) = S(\omega)C_g$, where $C_g$ is the group velocity. The wave amplitude can be calculated as $a(k) = \sqrt{2S(k)dk}$. The initial random sea states characterized by the spectral density $S(\omega)$ can thus be generated by assigning a random phase $\theta \in (0, 2\pi)$ to each wave in the domain.

For a given sea state, the initial surface elevation $\eta_i$ can be obtained from the spectral density function. Then the initial velocity potential $\phi_i$ can be calculated using the linear theory. Spurious modes develop when we use the linear solutions $(\eta_i, \phi_i)$ to solve the nonlinear wave evolution equations. To avoid this, we introduce the nonliearity gradually by multiplying a factor $\hat{W}$ with the nonlinear terms in Eq. (1) [62], where $\hat{W}$ increases from 0 to 1 in $T_{pre} = 5T_p$.

The waves we measured from satellite can travel in either direction. To take into account this factor, we consider waves travelling in the uniform positive x direction or random directions (i.e. positive and negative x directions), which is unidirectional and crossing sea state respectively. In practice, to generate crossing sea state, we assign a random number varying from (0,1) to a wave with wave number $k$, if this number is less than 0.5 this wave is travelling in positive x direction, otherwise the wave is travelling in negative x direction.

For a given sea state with the initial conditions $(\eta_i, \phi_i)$, we solve the wave evolution equations using phase resolve HOS up to $T = 30T_p$ and search for the rogue waves in the time window $5T_p < t < 30T_p$. $\mathscr{O}(100)$ rogue waves are screened out in each sea state so that we get the converged statistical properties (i.e. standard deviation with respect to the mean profile) of the rogue wave profile. The numerical parameters used in the simulations are $\delta x/\lambda_p$=0.018, 0.015 and 0.009 for sea state 4, 5 and 6, where $\lambda_p$ is the peak wavelength, time step $\delta t/T_p = 1/128$, nonlinearity M=4. The water depth is 300 m, which is in deep water region since the nondimensional parameter $k_p h > 10$ for sea state 4, 5 and 6.

## SPATIAL PROFILE

The database containing a large number of rogue waves is obtained for the initial wave field characterized by different sea states.

To show what an actual rogue wave look like we can shift the individual rogue wave to be peak centered and then take the average of the normalized profiles for large number rogue waves in the database (c.f. [33]). Fig.1(a) shows the averaged profile as well as the standard deviation for 48 distinct rogue waves in sea state 5 in the database. The averaged rogue wave profile is relatively symmetric with respect to the peak. Inspired by the fact that many field measured rogue waves are asymmetric in space, to preserve the rogue wave shape, we sort the rogue waves by the relative location of the peak and the trough. Along the wave propagation direction, we flip $\hat{\eta} = \eta/H_s$ in x if the trough comes first than the peak and hence $\hat{\eta}(\hat{x}) = \hat{\eta}(-\hat{x})$. Then the new collection of 48 rogue waves $\hat{\eta}$ is averaged and the standard deviation of the rogue waves respective to the mean profile is calculated, as shown in Fig. 1(b). We found that the rogue waves are actually not symmetric with respect to the peak, usually the rogue wave is followed or proceeded by a deeper trough.

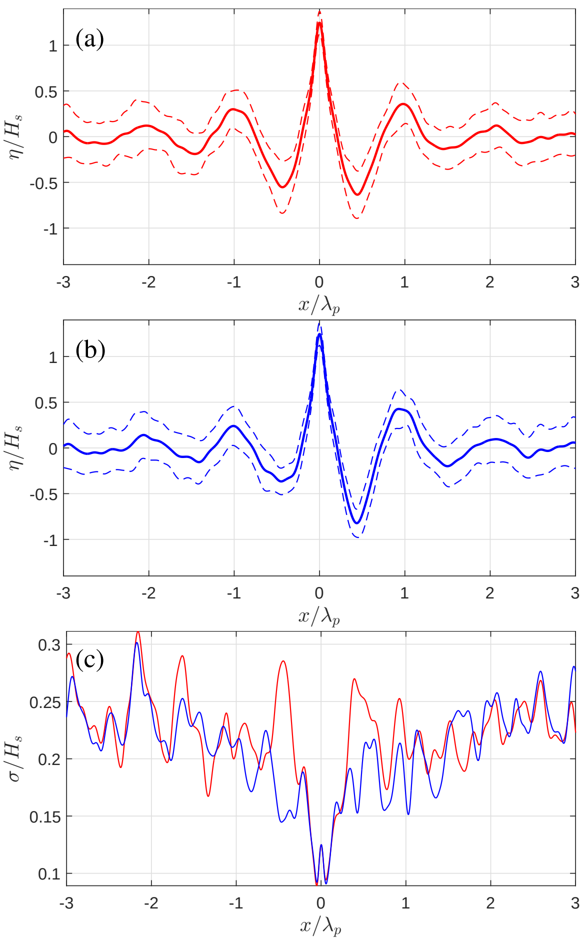

**FIGURE 1**. Are rogue waves spatially symmetric? We plot in figure (a) the average of 48 rogue waves obtained from the JONSWAP spectrum in the sea state 5. The averaged profile looks relatively symmetric (in agreement with [33]). In figure (b) we plot the average profile, but here we flip horizontally the profile of the rogue waves whose deep trough is on the left-hand side of their high crest. It turns out that this is the case in 20 out of 48 rogue waves obtained from our statistical analysis. In figures (a),(b) we also plot the standard deviation (note the contrast with standard error) plus/minus the average values (dashed lines). Figure (c) compares the standard deviation of the two cases in fig. a,b. Clearly the symmetric profile has a much higher standard deviation near the toughs on both sides of the high crest, suggesting that the actual spatial profile of the rogue wave is asymmetric and closer to that of figure (b) than figure (a).

The comparison of the standard deviation of the rogue wave profiles using these two approaches are plotted in Fig. 1(c). The symmetric profiles has a notably high standard deviation at the toughs both before and after the peak. Thus the actual rogue wave is indeed asymmetric and our approach is more appropriate in evaluating the properties of rogue wave profiles. In addition, as the sea becomes rougher (i.e. as the significant wave height increases), the rogue waves generally have larger height. However, surprisingly, the averaged profiles of the normalized rogue wave in sea state 4, 5 and 6 show identical shape. Besides the unidirectional sea states, we also consider the crossing sea states. The averaged profiles in crossing sea states in Fig. 2(b) and unidirectional seas in Fig. 2(a) match very well for the three sea states considered. This suggests that the normalized rogue wave profile in two-dimensional non-breaking sea states shows identical shape. The possible application of this observation could be in the design of ships and offshore structures (i.e. In the situation where the load from possible rogue waves need to be take into account, the identical rogue wave height $H_r$ and rogue wave trough to trough length $\lambda_r$ can be calculated based on the background sea state data).

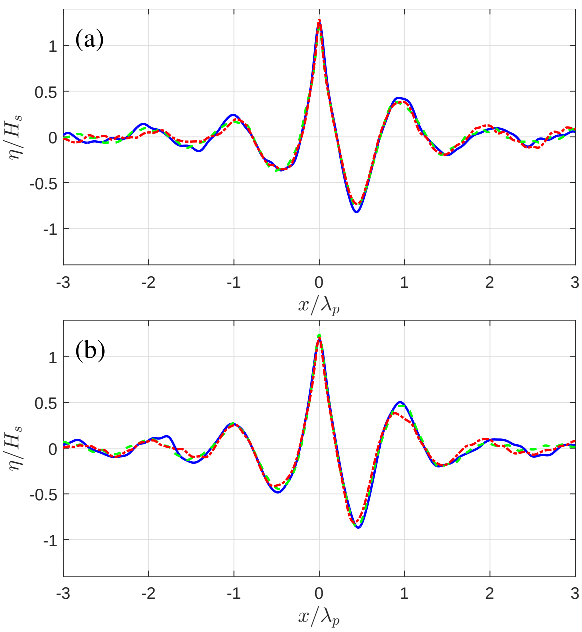

**FIGURE 2**. Comparison of statistically averaged profile of rogue waves in two-dimensional non-breaking unidirectional (fig a) and crossing (fig b) seas. Plotted are the average of rogue wave profile in sea states 4 (blue solid line), sea state 5 (green dashed line) and sea state 6 (red dash-dotted line). The $y$-axis is normalized by the significant wave height and the $x$-axis is normalized by the peak wavelength. The significant wave height is $H_s = 1.875$, 3.25 and 5 m in sea state 4, 5 and 6. The peak wave length $\lambda_p = 120.79$, 146.75 and 249.85 m. Clearly profiles match very well, and are similar in unidirectional and crossing seas.

## TEMPORAL PROFILE

Similarly, we obtain the statistical properties of the temporal rogue wave profiles. The time series is measured from a buoy which is fixed at the midpoint between the peak and trough for each rogue wave. This location is chosen because it is most likely to capture the features for both the peak and trough as the rogue wave propagates. We get 48 temporal rogue wave profiles in the sea state 5 and calculate the averaged profile using the direct averaging approach, as shown in Fig. 3(a), and the flipping and averaging approach, as shown in Fig. 3(b). Unlike the spatial rogue wave profiles, the difference in the temporal profile using these two approach is not significant. The standard deviations in Fig. 3(c) also show better agreement. Hence we can conclude that the rogue waves in time domain shows more symmetric feature than the rogue waves in spatial domain. This is in agreement with the field measured rogue waves, such as the *New Year Wave*.

## ACKNOWLEDGMENTS

This publication was made possible, in part, with the support from the American Bureau of Shipping, and the U.C. Berkeley Committee on Research. Computational resource for this research was provided by the National Energy Research Scientific Computing Center (NERSC) supported by the Office of Science, Department of Energy.

## CONCLUSIONS

To summarize, we obtain the identical profile of rogue waves in 2-dimensional non-breaking seas based on the statistical study on large number of rogue waves obtained from the direct simulation of the weakly nonlinear wave equations. Unlike the direct averaging approach adopted by Xiao [33], we propose to always keep the trough on the right side of the peak to preserve the shape of individual rogue wave and then take the average of them. We find that the averaged rogue wave profile has identical shape, height and wave length in both 2-D unidirectional and crossing seas. Moreover, the spatial profile is shown to be asymmetric respective to its peak, while the temporal profile is much more symmetric. This observation is in agreement with the field measured rogue waves, such as the *New Year Wave* [12] and the rogue waves measured in the Gulf of Tehuantepec [34].

In future, we also would like to consider the effect of the initial spectral density functions on the rogue wave profile. It is demonstrated that spectrum band width affects the rogue wave dynamics [63] and the wave statistics are deviated from the Gaussian statistics and hence yield higher probability in the formation of extreme waves when the band width is narrower [64]. The effect of the seabed topography, whether irregular (e.g. [65, 66] or with a prominent wavenumber (e.g. [67–70]), is known to potentially strongly influence the propagation of surface waves particularly in shallower waters. This is another important factor influencing the morphology of oceanic rogue waves that will be addressed elsewhere.

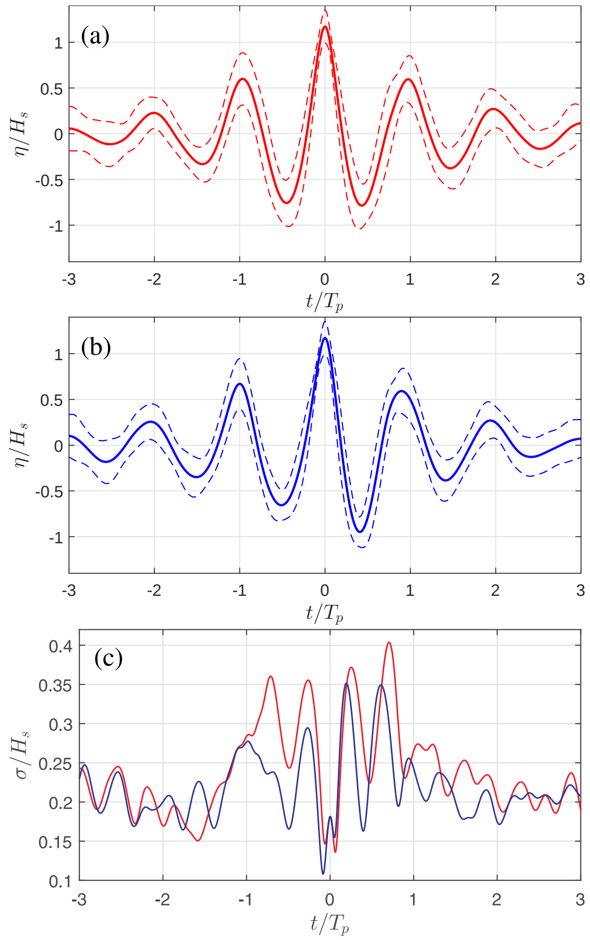

**FIGURE 3**. Statistically averaged temporal profile of rogue wave (as is measured from a fix buoy) from a JONSWAP spectrum in sea state 5. Figure (a) shows statistically averaged profile of 48 rogue waves. Figure (b) shows the average but by flipping the profile of the cases in which the deep trough comes ahead of the high crest (in time). We also plot in both figures the average values plus/minus the standard deviation (dashed lines), and standard deviation are plotted in figure c for a better cross comparison. Clearly the difference is much less than the spatial profile case. We can conclude that measurement of a rogue wave in time on average look more symmetric than its profile in space.

## REFERENCES

[1] Mallory, J., 1974. “ABNORMAL WAVES on the south east coast of south africa”. *International Hydrographic Review,* ***51***, pp. 99–129.

[2] Toffoli, a., Lefèvre, J. M., Bitner-Gregersen, E., and Monbaliu, J., 2005. “Towards the identification of warning criteria: Analysis of a ship accident database”. *Applied Ocean Research,* ***27***(6), pp. 281–291.

[3] Faulkner, D. “Shipping safety A matter of concern”. *Review Literature And Arts Of The Americas*.

[4] Ersdal, G., Kvitrud, a., Chung, J. S., Frederking, R. M. W., Saeki, H., and Koterayama, W., 2000. "Green water on Norwegian production ships". *Proceedings of the 10th (2000) International Offshore and Polar Engineering Conference, Vol I,* ***1***, pp. 211–218.

[5] Pelinovsky, E., and Kharif, C., 2008. *Extreme ocean waves*.

[6] Erkintalo, M., 2015. "Rogue waves: Predicting the unpredictable?". *Nature Photonics,* ***9***(9), pp. 560–562.

[7] Haver, S., 2004. "A Possible Freak Wave Event Measured at the Draupner Jacket January 1 1995". *Rogue Waves 2004*.

[8] Taylor, P. H., 1995. "The shape of the Draupner Wave of 1st January 1995".

[9] Guedes Soares, C., Cherneva, Z., and Antao, E. M., 2003. "Characteristics of abnormal waves in North Sea storm sea states". *Applied Ocean Research,* ***25***(2003), pp. 337–344.

[10] Slunyaev, a., Pelinovsky, E., and Guedes Soares, C., 2005. "Modeling freak waves from the North Sea". *Applied Ocean Research,* ***27***(1), pp. 12–22.

[11] Clauss, G. F., Klein, M., and Testa, D., 2008. "Spatial Evolution of an Extreme Sea State With an Embedded Rogue Wave". *Volume 4: Ocean Engineering; Offshore Renewable Energy*, pp. 149–156.

[12] Klein, M., and Clauss, G., 2011. "The New Year Wave in a seakeeping basin: Generation, propagation, kinematics and dynamics". *Ocean Engineering,* ***38***(14-15), pp. 1624–1639.

[13] Pelinovsky, E., Slunyaev, A., Lopatoukhin, L., Divinsky, B., and Levin, B., 2001. "Freak Wave Event in the Black Sea : observation and modeling". *Dokl Earth Sci2004 A*(395), pp. 5–6.

[14] Lehner, S., Schulz-Stellenfleth, J., and Niedermeier, A., 2002. "Detection of extreme waves using synthetic aperture radar images". *Geoscience and Remote Sensing Symposium, 2002. IGARSS '02. 2002 IEEE International,* ***3***(1), pp. 1893—-1895vol.3.

[15] Christou, M., and Ewans, K., 2014. "Field Measurements of Rogue Water Waves". *Journal of Physical Oceanography,* ***44***(9), pp. 2317–2335.

[16] Kharif, C., and Pelinovsky, E., 2003. "Physical mechanisms of the rogue wave phenomenon". *European Journal of Mechanics - B/Fluids,* ***22***(6), nov, pp. 603–634.

[17] Dysthe, K. B., Krogstad, H. E., and Müller, P., 2008. "Oceanic Rogue Waves". *Annual Review of Fluid Mechanics,* ***40***(1), pp. 287–310.

[18] Chabchoub, a., Hoffmann, N. P., and Akhmediev, N., 2012. "Observation of rogue wave holes in a water wave tank". *Journal of Geophysical Research,* ***117***(November 2011), feb, p. C00J02.

[19] Chabchoub, a., and Akhmediev, N., 2013. "Observation of rogue wave triplets in water waves". *Physics Letters A,* ***377***(38), pp. 2590–2593.

[20] Clauss, G. F., Schmittner, C. E., and Hennig, J., 2008. "Systematically Varied Rogue Wave Sequences for the Experimental Investigation of Extreme Structure Behavior". *Journal of Offshore Mechanics and Arctic Engineering,* ***130***(2), p. 021009.

[21] Clauss, F., G., Klein, Marco, Onorato, and Miguel, 2011. "Formation of Extraordinarily High Waves in Space and Time". *Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering*.

[22] Faulkner, D., 1998. "An Independent Assessment of the Sinking of the MV DERBYSHIRE". pp. 59–103.

[23] Corte, C., and Grilli, S. T., 2006. "Numerical modeling of extreme wave slamming on cylindrical offshore support structures". *Proceedings of the 16th International Offshore and Polar Engineering Conference,* ***4***, pp. 394–401.

[24] Clauss, G. F., Schmittner, C. E., and Hennig, J., 2008. "Systematically Varied Rogue Wave Sequences for the Experimental Investigation of Extreme Structure Behavior". *Journal of Offshore Mechanics and Arctic Engineering,* ***130***(2), p. 021009.

[25] Mori, N., Yasuda, T., and Nakayama, S.-i., 2000. "Statistical properties of freak waves observed in the sea of Japan". *Tenth (2000) International Offshore and Polar Engineering Conference,* ***4***, pp. 109–115.

[26] Taylor, P. H., and Adcock, T., 2006. "Draupner Giant Wave of 1St January 1995 and the Associated Sea-State, and How To Estimate Directional Spreading From an Eulerian Surface Elevation Time History". *... Workshop on Wave ...* (January 1995).

[27] Guedes Soares, C., and Pascoal, R., 2005. "On the Profile of Large Ocean Waves". *Journal of Offshore Mechanics and Arctic Engineering,* ***127***(4), p. 306.

[28] Chabchoub, a., Hoffmann, N. P., and Akhmediev, N., 2011. "Rogue Wave Observation in a Water Wave Tank". *Physical Review Letters,* ***106***(20), may, p. 204502.

[29] Chabchoub, a., Hoffmann, N., Onorato, M., Slunyaev, a., Sergeeva, a., Pelinovsky, E., and Akhmediev, N., 2012. "Observation of a hierarchy of up to fifth-order rogue waves in a water tank". *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics,* ***86***(5), pp. 1–6.

[30] Wu, G., Liu, Y., and Yue, D. K. P., 2005. "Studying rogue waves using large-scale direct phase-resolved simulations". *Proc. 14th Aha Hulikoa Winter Workshop, Rogue Waves*, pp. 101–107.

[31] Fochesato, C., Grilli, S., and Dias, F., 2007. "Numerical modeling of extreme rogue waves generated by directional energy focusing". *Wave Motion,* ***44***(5), apr, pp. 395–416.

[32] Gibson, R., and Swan, C., 2007. "The evolution of large ocean waves: the role of local and rapid spectral changes". *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences,* ***463***(2077), pp. 21–48.

[33] Xiao, W., Liu, Y., Wu, G., and Yue, D. K. P., 2013. "Rogue wave occurrence and dynamics by direct simulations of

nonlinear wave-field evolution". *Journal of Fluid Mechanics,* ***720***, pp. 357–392.

[34] Melville, W. K., Romero, L., and Kleiss, J. M., 2005. "Extreme wave events in the Gulf of Tehuantepec". *Proceedings of the 14th Aha Hulikoa Hawaiian Winter Workshop on Rogue Waves*, pp. 23–28.

[35] Onorato, M., Osborne, A. R., Serio, M., and Bertone, S., 2001. "Freak Waves in Random Oceanic Sea States". *Physical Review Letters,* ***86***(25), pp. 5831–5834.

[36] Alam, M.-r., 2014. "Predictability horizon of oceanic rogue waves". *Geophysical Research Letters,* ***41***, pp. 1–9.

[37] Toffoli, A., Monbaliu, J., Lefevre, J. M., and Bitner-Gregersen, E., 2004. "Dangerous sea-states for marine operations". pp. 85–92.

[38] Cavaleri, L., Bertotti, L., Torrisi, L., Bitner-Gregersen, E., Serio, M., and Onorato, M., 2012. "Rogue waves in crossing seas: The Louis Majesty accident". *Journal of Geophysical Research: Oceans,* ***117***(5), pp. 1–8.

[39] Magnusson, A. K., 1989. "Forecasting Extreme Waves in Practice". p. 2007.

[40] Toffoli, a., Bitner-Gregersen, E. M., Osborne, a. R., Serio, M., Monbaliu, J., and Onorato, M., 2011. "Extreme waves in random crossing seas: Laboratory experiments and numerical simulations". *Geophysical Research Letters,* ***38***, pp. 1–5.

[41] Hasselmann, K., Barnett, T., Bouws, E., and Carlson, H., 1973. "Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project". *Deutsches Hydrographisches Institut - Hamburg*.

[42] Islas, A., and Schober, C., 2005. "Predicting rogue waves in random oceanic sea states". *Physics of Fluids*(October 2004), pp. 18–21.

[43] Chalikov, D., 2009. "Freak waves: Their occurrence and probability". *Physics of Fluids,* ***21***(7), p. 076602.

[44] Waseda, T., 2006. "Evolution of random directional wave and rogue wave occurrence". pp. 1–16.

[45] Zakharov, V. E., 1968. "STABILITY OF PERIODIC WAVES OF FINITE AMPLITUDE ON THE SURFACE OF A DEEP FLUID". *Journal of Applied Mechanics and Technical Physics,* ***9***(2), pp. 190–194.

[46] Dommermuth, D. G., and Yue, D. K. P., 1987. "A high-order spectral method for the study of nonlinear gravity waves". *Journal of Fluid Mechanics,* ***184***, apr, p. 267.

[47] West, B. J., Brueckner, K. A., Janda, R. S., Milder, D. M., and Milton, R. L., 1987. "A new numerical method for surface hydrodynamics". *Journal of Geophysical Research: Oceans,* ***92***(C11), pp. 11803–11824.

[48] LIU, Y., and YUE, D. K., 1998. "On generalized Bragg scattering of surface waves by bottom ripples". *Journal of Fluid Mechanics,* ***356***, pp. 297–326.

[49] Alam, M.-R., Liu, Y., and Yue, D. K., 2010. "Oblique sub-and super-harmonic bragg resonance of surface waves by bottom ripples". *Journal of Fluid Mechanics,* ***643***, pp. 437–447.

[50] Alam, M.-R., Liu, Y., and Yue, D. K., 2011. "Attenuation of short surface waves by the sea floor via nonlinear subharmonic interaction". *Journal of Fluid Mechanics,* ***689***, pp. 529–540.

[51] Alam, M.-R., Liu, Y., and Yue, D. K., 2009. "Bragg resonance of waves in a two-layer fluid propagating over bottom ripples. part i. perturbation analysis". *Journal of Fluid Mechanics,* ***624***, pp. 191–224.

[52] Alam, M.-R., Liu, Y., and Yue, D. K., 2009. "Bragg resonance of waves in a two-layer fluid propagating over bottom ripples. part ii. numerical simulation". *Journal of Fluid Mechanics,* ***624***, pp. 225–253.

[53] Alam, M.-R., Liu, Y., and Yue, D. K., 2009. "Waves due to an oscillating and translating disturbance in a two-layer density-stratified fluid". *Journal of Engineering Mathematics,* ***65***(2), pp. 179–200.

[54] Alam, M.-R., Liu, Y., and Yue, D. K., 2011. "Resonant-wave signature of an oscillating and translating disturbance in a two-layer density stratified fluid". *Journal of Fluid Mechanics,* ***675***, pp. 477–494.

[55] Alam, M.-R., 2012. "Broadband cloaking in stratified seas". *Physical review letters,* ***108***(8), p. 084502.

[56] Alam, M.-R., 2012. "Nonlinear analysis of an actuated seafloor-mounted carpet for a high-performance wave energy extraction". *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences,* ***468***(2146), pp. 3153–3171.

[57] Alam, M.-R., 2012. "A flexible seafloor carpet for high-performance wave energy extraction". In ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering, American Society of Mechanical Engineers, pp. 839–846.

[58] Toffoli, A., Gramstad, O., Trulsen, K., Monbaliu, J., Bitner-Gregersen, E., and Onorato, M., 2010. "Evolution of weakly nonlinear random directional waves: laboratory experiments and numerical simulations". *Journal of Fluid Mechanics,* ***664***, pp. 313–336.

[59] Alam, M.-R., 2012. "A new triad resonance between co-propagating surface and interfacial waves". *Journal of Fluid Mechanics,* ***691***, pp. 267–278.

[60] Alam, M.-R., 2014. "Predictability horizon of oceanic rogue waves". *Geophysical Research Letters,* ***41***(23), pp. 8477–8485.

[61] Carter, D., 1982. Estimation of wave spectra from wave height and period. Tech. rep.

[62] Wu, G., 2004. "Direct simulation and deterministic prediction of large-scale nonlinear ocean wave-field". PhD thesis, Massachusetts Institute of Technology, Cambridge, MA.

[63] Shemer, L., Sergeeva, A., and Liberzon, D., 2010. "Effect of the initial spectrum on the spatial evolution of statis-

tics of unidirectional nonlinear random waves". *Journal of Geophysical Research: Oceans,* ***115***(12), pp. 1–12.

[64] Onorato, M., Osborne, A. R., and Serio, M., 2006. "Modulational instability in crossing sea states: A possible mechanism for the formation of freak waves". *Physical Review Letters,* ***96***(1), pp. 1–4.

[65] Alam, M.-R., and Mei, C. C., 2007. "Attenuation of long interfacial waves over a randomly rough seabed". *Journal of Fluid Mechanics,* ***587***, pp. 73–96.

[66] Alam, M.-R., and Mei, C. C., 2008. "Ships advancing near the critical speed in a shallow channel with a randomly uneven bed". *Journal of Fluid Mechanics,* ***616***, pp. 397–417.

[67] Couston, L.-A., Guo, Q., Chamanzar, M., and Alam, M.-R., 2015. "Fabry-perot resonance of water waves". *Physical Review E,* ***92***(4), p. 043015.

[68] Zareei, A., and Alam, M.-R., 2015. "Cloaking in shallow-water waves via nonlinear medium transformation". *Journal of Fluid Mechanics,* ***778***, pp. 273–287.

[69] Elandt, R. B., Couston, L.-A., Lambert, R. A., and Alam, M.-R., 2015. "Bragg resonance of gravity waves and ocean renewable energy". In *Integrated Systems: Innovations and Applications*. Springer, pp. 211–225.

[70] Elandt, R. B., Shakeri, M., and Alam, M.-R., 2014. "Surface gravity-wave lensing". *Physical Review E,* ***89***(2), p. 023012.