

Results of the MAXWAVE project

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Abstract. Heavy sea states and severe weather conditions have caused the loss of more than 200 super carriers within the last 20 years. In many cases single 'rogue waves' of abnormal height as well as groups of extreme waves have been reported by crew members of such vessels. The European Project MAXWAVE deals with both theoretical aspects of extreme waves as well as new techniques to observe these waves using different remote sensing techniques. The final goal was to improve the understanding of the physical processes responsible for the generation of extreme waves and to identify geophysical conditions in which such waves are most likely to occur. New radar data were used to compile a census on wave statistics with respect to those extreme wave events and to improve prediction of such events. Several ship and offshore platform accidents are analysed and the impact on ship and offshore design is discussed.

Introduction

The existence of rogue waves was doubted for a long time, but photography, satellite imagery and continuous observations at the North Sea oil platforms showed many cases of such extremely high waves. In engineering science, rogue waves are usually defined by a maximum wave height of more than two times the significant wave height. According to Raleigh statistics, this is extremely unlikely to happen in a 20 minute buoy time series.

Figure 1 is a famous photograph archived in the NOAA historical picture gallery, showing a white wall of water as one example of an individual abnormal wave.

The new spatial radar measurements used in Max-wave made it possible to observe rogue waves on a global scale. Extreme waves were among strong currents, in the South Atlantic and under hurricane conditions. Additionally these measurements showed that for spatial data covering a large area, other criteria for extreme events have to be used than $H_{max} / H_{sig} > 2$ because many more individual crests are being observed than in a standard buoy time series.

Figure 2 is a measured time series of wave elevation, the Draupner wave, measured on January 1, 1995, at the Draupner platform (58.1°N, 2.28°E) located in the North Sea.

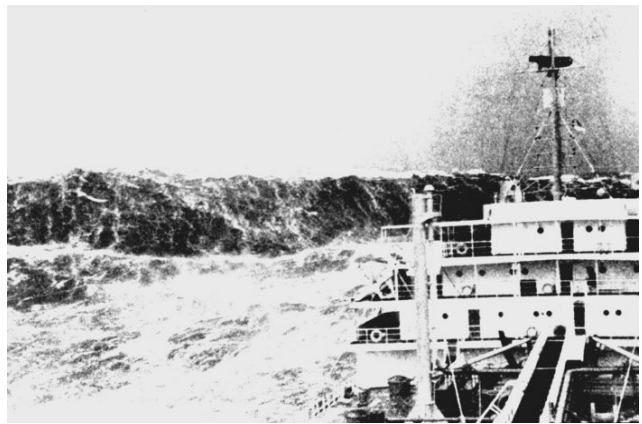


Figure 1. Extreme wave event (white wall). The picture was taken from a merchant vessel in the Bay of Biscay (see NOAA ©, picture gallery).

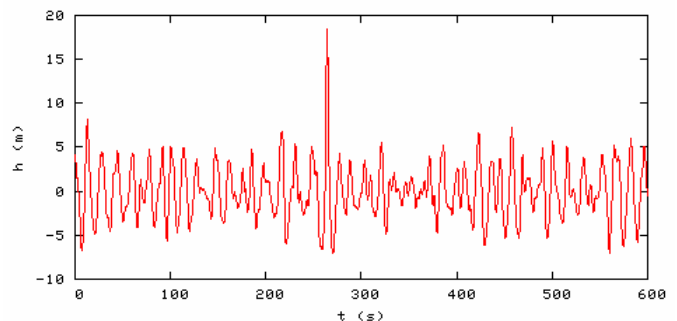


Figure 2. The Draupner wave, January, 1, 1995.

This is one of the cases that prove the existence of giant individual waves that are more than two times higher than the significant wave height. Satellite images of the Draupner field from January 1, 1995, showed several extreme wave events in the 100 x 100 km area around the field. On the satellite image it could also be observed that the directional spectra had two peaks and thus crossing seas were generating the extreme wave.

Scope of Maxwave

This paper aims at giving an overview on the research performed during the Maxwave project. The main tasks performed within the project are these:

To confirm the existence of rogue waves and their risk of encounter. Existing measurements and hindcast modelling is used to better understand the shape and impacts of extreme waves in relation with ship/offshore accidents. Modern measurement techniques are exploited towards the recognition of extreme individual waves and their regional probability of occurrence.

To implement the improved knowledge of freak waves to modern ship design, by involving the two communities of marine design and oceanography.

To develop forecast criteria for rogue waves with the aid of physical, mathematical statistical and deterministic wave model tests and by that to improve security for human life.

To disseminate and exploit the project results by the project members, covering the marine design/operation side, the wave science community, system providers and certifying institutions.

Partners of the project were three European meteorological offices, one classification agency, one SME, three universities and two large research facilities, see Table 1.

The different workpackages of Maxwave are dealing as well with oceanographic investigations of extreme events and statistics of ship accidents, as with impacts for ship and offshore design and socio-economic consequences.

A summary of the workpackages is given in the following chapters, further results can be found on the web page: w3g.gkss.de/projects/maxwave.

Table 1. Partners of the project

GKSS Research Center, Germany
Institute of Hydroengineering, Polish Academy of Sciences
Norwegian Meteorological Institute (Met No)
German Aerospace Center (DLR)
UK Meteorological Office
Instituto Superior Tecnico (IST), Portugal
Meteo France
Ocean Waves, Germany
Catholic University of Leuven, Belgium
Technical University of Berlin, Germany
Det Norske Veritas (DNV), Norway

Investigation on extreme single waves (GKSS)

Formal mathematical expressions for the description of the properties of Maxwaves have been developed. They rely on the superposition of elementary waves that are characterized by the dispersion relation of ocean waves.

The visual classification of the three types

1. Singular Wave Tower
2. Three Sisters
3. White Wall

is mapped on three types of Fourier decompositions in space and time. We describe the types and tentative generation mechanisms.

A modified delta-type function in space and time that propagates with all Fourier components same direction seems to be a convenient model for type 1 (Singular Wave Tower). This wave type can be generated by oceanic focussing/defocussing processes as occurring in currents, see *Lavrenov (1998)*.

Type 2 is described by a carrier wave, modulated by a wave group of finite length given by the order of three wave crests. These wave groups can receive energy from the atmosphere by extended squall lines travelling in the propagation direction of the group.

Type 3 is a stationary interference pattern that is similar to a wave pattern created by a ship. It can be generated by the encounter of wind sea systems with similar wave lengths but different directions (cross seas) or by small scale disturbances inside storm areas. Figure

3 shows such a stable extreme wave group that has the form of a ship wake. It can be generated from a standard JONSWAP spectrum with a horseshoe type directional distribution (Lehner *et al.*, 2004).

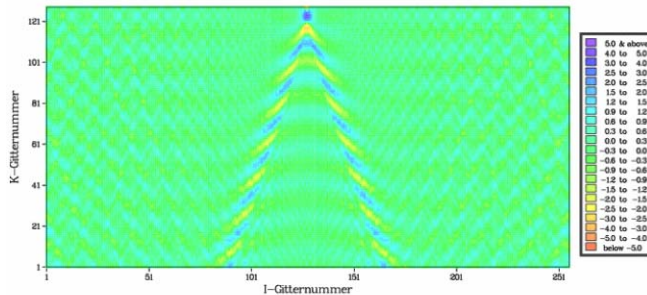


Figure 3. Stable extreme wave group of a ship wake like pattern generated from a standard JONSWAP spectrum.

New insights in the dynamical behaviour of ocean surfaces have been gained using radar from ships, land based towers, and satellites. It is concluded that the statistical description by wave spectra as in standard wave models cannot reproduce transient forces exerted by singular space-time-events.

Extreme wave statistics by use of in-situ data (MetNo)

Several storm cases were chosen on the basis of knowledge of ship accidents from the Lloyds accident database provided through DNV and available information of abnormal or unexpected wave hits on offshore structures in the North Sea. In-situ measurements of wave profiles from Ekofisk and the Draupner platform were used in a statistical study and analysed for the purpose of defining forecasting methods.

A thorough study showed that what seemed to be abnormal waves could be predicted in statistical models using 2nd order theory. with one exception: the famous “Draupner” wave, where the crest-to-height factor was above 1.5. Analysis of spectral parameters calculated from the time series including high crests was performed in several ways, all leading to the conclusion that simultaneous occurrence of Maxwaves and a high (or low) value of any indicator could not be proven. The indicators tested included a high JONSWAP gamma (peakedness factor in the JONSWAP spectrum), and a high Benjamin-Feir instability index, both being presented in the literature as indicators for Maxwaves (Janssen, 2003).

Extreme wave statistics from radar data sets (DLR)

An advantage when measuring sea state by marine and satellite radar (SAR) is the possibility to retrieve the full two-dimensional ocean wave spectrum, i.e., wind sea and different swell peaks can be separated and their significant wave height and mean direction estimated.

As a first step, algorithms to estimate mean sea state parameters from satellite radar images were improved and tested in collaboration with the French Meteorological Office and the UK Meteorological Office. Marine radar data were gathered on ship journeys to areas of expected high sea state. Satellite SAR data were reprocessed to 5x10 km images with global coverage of about one thousand daily, for a period of three weeks during southern winter and in hurricane season (Lehner, 2000). Thus it was possible to investigate extreme wave events on a global scale.

The aim was to extend wave measurements from the spectral wave description to single events, (see Figure 4). During the project, methods were developed that allow the estimation of variation of the local sea surface (Dankert and Rosenthal, 2003; Schulz-Stellenfleth and Lehner, 2004). Further details on the radar measurements of rogue waves can be found in Lehner, these proceedings.

In addition, new techniques of wave group detection and crest length derivation in two dimensions have been carried out.

Analysis of ship accidents - databases and hindcasts (UK Met Office)

The main objective of this work package to date has been to analyse the sea state conditions at the time and place of Maxwaves events in order to identify conditions that give a high likelihood of Maxwaves occurrence. Ship casualty databases were screened to identify several cases possibly due to rogue waves. Hindcasts were run for the following cases: Draupner (New Years Day wave, 1/1/95), Stenfjell (26/10/98) and Schiehallion (9/11/98). All hindcasts had high temporal (30 minutes) and spatial (12 km) resolution, by using a limited-area spectral model over the northeast Atlantic. As one candidate for the mechanism for rogue wave development, the Benjamin-Feir instability was used to develop a diagnostic parameter derivable both from observations and from spectral wave model output. The degree of peak enhancement of the wave energy frequency spectrum was used as a measure of the Benja-

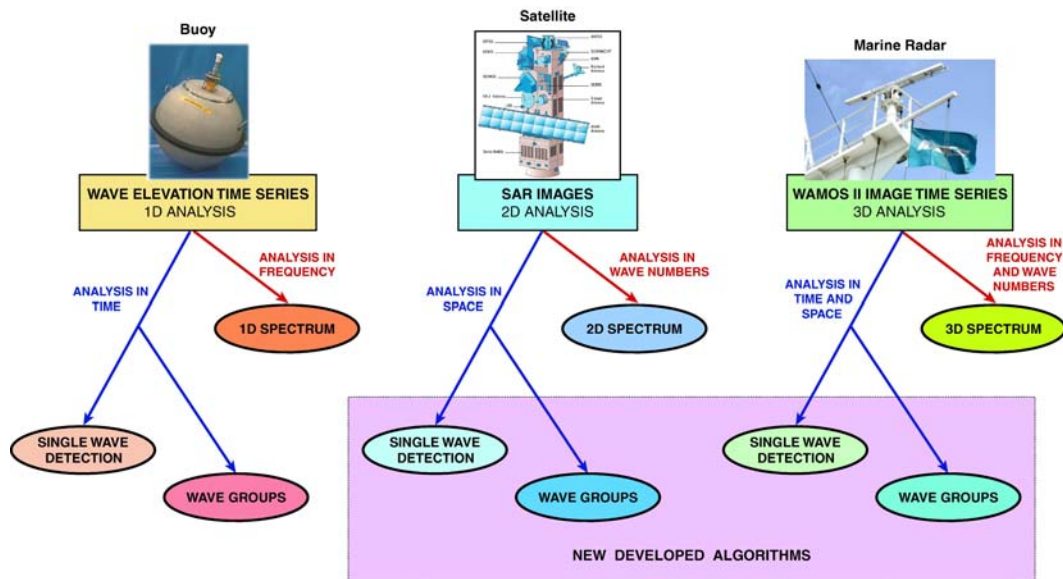


Figure 4. Instruments used and algorithms developed during the MAXWAVE project.

min-Feir instability. Further a method of fitting JONSWAP gamma to an arbitrary spectrum was developed. An analysis of the behaviour of gamma during high sea-state conditions was performed. Very high (6-8) values of gamma were computed from observed time-series of wave height under rapidly changing conditions (Magnusson and Gunson, 2002).

Regional distribution of Maxwaves (Catholic University of Leuven)

The main objective of this workpackage is to generate a risk map for the encounter of rogue waves. It is assumed that the risk for encounter for a rogue, defined as the probability of occurrence, can be enhanced by physical processes like depth refraction and strong currents or by weather events, like rapid and severe developments in winter storms. Two approaches have been taken: globe covering individual analysis of remotely sensed SAR-images and the exploration of ship accidents due to heavy weather.

A database that contains ship accidents due to heavy weather was extracted from Lloyd's Marine Information Service (LMIS). Searching for clues and assuming that a 'Maxwave' could be a cause, the wave spectra before and at the time of the accidents might provide risk indicators. Therefore sea-state parameters were retrieved from the ECMWF-archive. The correlation analysis between casualties and sea-state indicates that the classical spectral parameters (H_s , T_p) are not sufficient to point at unusual extreme phenomena. However, there

are indications that particular combinations of wind sea and swell and rapidly changing conditions in the sea-state can create dangerous situations. Figure 5 shows an accident map based Hapag Loyds database. For details and further accident maps see Soares *et al.* (2001) and Toffoli and Monbaliu (2003).

World Wide Ship Accidents (1995-1999)

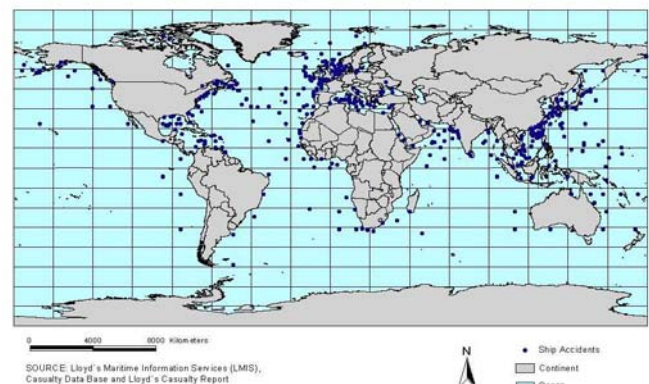


Figure 5. Ship accidents between 1995 and 1999 from Hapag Loyds accident database.

Wave conditions for ship design (IST)

Figure 6 shows the impact on the bow of MV Wilstar, which was hit by a rogue wave in the Algulhas current.

To develop a consistent approach for the design of the ship hull girder against the loads induced by large

episodic waves, it is necessary to be able to predict the likelihood of encountering such waves and also to predict the effects they induce on the hull.



Figure 6. The *Wilstar*, which was hit by a rogue wave in the Algulhas current.

In the Maxwave project it was demonstrated that given one such wave in a time series it is possible to determine its effects on ships.

Different authors have suggested that extremely high waves may be generated by different mechanisms, but all mechanisms that can lead to these waves are not fully identified and understood. Whatever the nature of the generation process, the designers and operators of marine structures require information about the probability of encounter and the representative shapes of these large waves so that they can be appropriately considered in design.

Wave criteria for offshore structures (Technical University of Berlin)

The Technical University of Berlin developed a numerical technique for the analysis and simulation of Maxwaves in a numerical wave flume. The underlying numerical simulation method is based on potential flow theory and applies the finite element method. With this method, two-dimensional extreme design waves can be optimized. The main advantage of this approach is that local wave parameters such as wave height, wave length and crest elevation can be taken into account (Claus *et al.*, 2003).

One example for investigating wave-structure interaction of marine structures is a semisubmersible drilling platform which has been simulated in a wave sequence with varying rogue wave heights of the embedded waves (Claus *et al.*, 2003). The results of this investigation point out, that maximum response is directly re-

lated to the Maxwaves height. However, the response increase is clearly lower than the wave height increase. Similar tests have been carried out with a model of an FPSO in cooperation with Instituto Superior Técnico, where motion behaviour and bending moments at two cross sections have been investigated. A comparison of experimental and numerical results with the traditional frequency-domain approach for design reveals that the existing design rules are sufficient to cover the simulated events.



Figure 7. Extreme wave reproduced in the Hannover wave tank.

Definition of ‘warning criteria’ (Meteo France)

One interesting point found when defining dangerous sea state conditions in which accidents happened is that fast temporal variations of sea state parameters are observed close to the accident time. Also, for most of the cases, accidents occur during crossing sea conditions, or just after crossing sea conditions, when the swell and the wind sea are just “almost” aligned.

This leads to the definition by Meteo France of a new cross sea index used as a warning criterion (Toffoli *et al.*, 2003).

$$CSI \equiv H_s/2 * \exp\left(-10 \cdot (\text{spread} - 1)^2\right)$$

Official warning criteria

The team agreed to propose relevant amendments to the Manual on Marine Meteorological Services (WMO-No. 558).

In paragraph 2.2.4 of the MMMS (Warnings), it says: “Warnings for other severe conditions such as poor

visibility, severe swell, risk of abnormal waves, ice accretion, etc., shall also be issued, as necessary.”

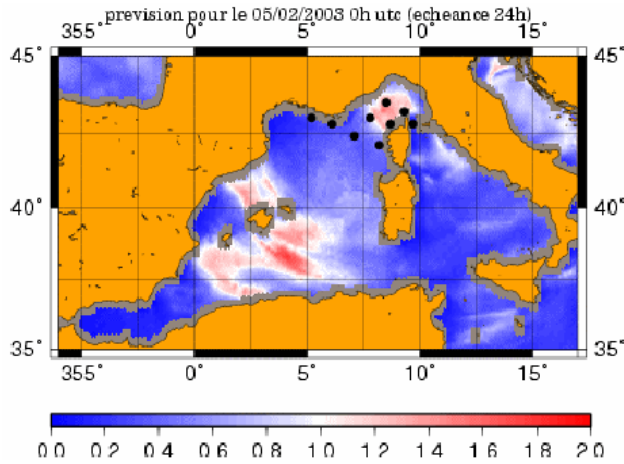


Figure 8. Cross Sea Index for the Mediterranean as defined by the French Meteorological Office, for May 2, 2003

In paragraph 2.2.6 (Forecasts), the following sentence should be added at the end of 2.2.6.1.1 : “in addition, phenomena like breaking seas, cross seas and risk of abnormal/Maxwaves waves shall also be included, if needed and feasible.”

Socio-economic assessment (DNV)

The state-of-the-art review on wave knowledge in current design and operational practice has been developed. Extreme severe wave conditions have been discussed in perspective to the existing design and operational criteria. The study has been primarily concentrated on ships; however, some aspects of offshore structures design have also been considered; see Maxwave webpage for a thorough review of the state of the art and *Bitner-Gregersen (1997, 2003)*.

The Norwegian offshore standards take into account extreme severe wave conditions by requiring that a 10,000-year wave does not endanger the structure’s integrity (Accidental Limit State, ALS). Consensus needs to be reached within the offshore industry on wave models for prediction of rogue waves and design scenarios that should be included in ALS. Critical Maxwave parameters are, e.g., maximum crest, wave steepness, wave asymmetry and the directional wave spectrum.

So far, rogue waves are not explicitly accounted for in Classification Societies’ Rules for ships’ design, due to insufficient knowledge about these waves and ship response or the probability of ships encountering such

waves. The project has demonstrated the importance of the use of time domain codes to calculate wave-induced loads on ships in severe weather.

Warning criteria for rogue waves are welcomed by the offshore and shipping industry to be included in weather services (e.g. important for determining a ship route in accordance with Serviceability Limit State (SLS)). A large step towards reaching this goal is already made by the Maxwave project. Classification societies are developing shipboard routing assistance systems where warning criteria can be incorporated.

Conclusions and outlook

Due to the high number of ship accidents caused by severe sea states and the observed encounters with high waves at offshore platforms, there is a necessity to find an explanation and prediction for rogue wave phenomena.

New datasets like time series of images from a marine radar yield consecutive spatial images of ocean waves and thus insight into the development of crests of extreme waves. The global satellite data can be used to investigate extreme wave statistics in areas in which none or only a paucity of in situ measurements existed up to now. For this data set, acquired during the southern winter a highest wave of about 28 meters was found in the South Atlantic.

An explanation for such extreme events can be given by linear theory constructing stable extreme waves (Phase rogues) by superposition of waves coming from two storms or different parts in an extended storm. Another explanation based on nonlinear focussing of energy from different spectral bands as e.g., described by the Benjamin Feir Index could up to now not be confirmed by the radar and buoy data, but is still under investigation for longer datasets.

Ship accidents were found to happen mainly in fast changing sea state conditions and in cases of crossing seas. As a consequence a new cross-sea index was defined by the French meteorological office.

The major effect of rogue waves on ships was found to be broken windows with subsequent flooding and engine failure or broken hatch locks.

Warning criteria against rogue waves are welcomed by the offshore and shipping industry to be introduced in weather services. A large step towards reaching this goal is already accomplished by the Maxwave project.

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