# FREAK WAVE GENERATION AND THEIR PROBABILITY

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## Abstract

The problem of extreme wave estimation is crucial at last 25-30 years due to active using of ocean resources. Mainly the attention paid to estimation of extreme waves in the fixed spatial point of the sea. But for ship navigations, transport operations, offshore supplying etc. estimates of the spatial occurrences of extreme waves are required. In these cases spatiotemporal variability of wave fields is of special interest.

One of the most interesting extreme phenomena is freak (or rogue) waves. These one are anomaly steep and high waves. The probability of freak waves generation depends from a lot of internal (modulation, nonlinearities, etc.) and external (metocean) factors. Spatial dimensions of the sea region increase the probability of ship encounter with a freak wave. Classical statistical analysis of time series do not allows estimating the probabilities of freak waves occurrence and associated weather conditions.

Main definitions of freak waves, reasons of appearance, possibility of generation in the sea and approach to estimation is presented.

## 1. INTRODUCTION

Problem of extreme (high) wave height in the World Ocean exist as long as mankind utilize seas and oceans. Estimates of extreme waves changed from enormous 50 meters up to unassuming 6-7 meters. The problem of reliable estimates of highest waves became especially important in the last 25-30 years. This is connected with active developing of sea resources in shelf zones and intensive navigation. There are some fundamental successes in the approaches to extreme wave estimation. Now days, it is known, in principal, how to estimate wave height with return period 10, 50, 100, and even 1000 years [1,2]. Such estimates are made for a great number of gas and oil fields all over the World Ocean. Review of existing approaches to extreme wave estimation published (inter alia) by World Meteorological Organization [2]. Extreme waves estimates are component of the wave climate. At present time it is well known, that wave heights may be as high as 30 (m). Such wave had been measured in some places, e.g. in the North Sea. In the Barents Sea wave with 100 years return period is 24 (m), in the North Sea about 30 (m). High waves are not so rare events and in principal not dangerous. But among extreme waves may occur waves, which are really dangerous. Such waves are not included to any design specific codes and not in accordance with existing wave theories. These waves are known by accidents with ships and oilrigs. During last decade such waves had been measured in some places [3]. These waves are known as freak or rogue or even as wave-killer. The map with possible arising of freak waves is presented in the fig. 1. In reality this map do not reveal all the regions where freak wave may arise. In particularly, three such waves had been recorded in the Black sea (see fig. 2). Among the areas, in the fig. 1 the most famous is the region near SE coast of Africa (number 13 on the fig.). Freak wave near this region is known as cape rollers [5]. Importance of freak wave investigations had been marked in a lot of international conferences (see e.g. [3,6,7]). Special conference had been devoted to this problem [8].

## 2. MAIN DEFINITIONS OF FREAK WAVES

There is no common definition of a freak wave. The most simple is, that the wave with the height $h>2h_s$ is freak. In this case for Rayleigh wave height distribution such a wave will be one from 3000.

With the mean period 10s, such a wave will arise every 8 hours. It seems, that even the condition $h>2.5h_s$ is too weak. Therefore, additional criteria are introduced. They are concerns the wave form and it position among other waves. In the table 1 the basic definitions are presented.

The main features of freak waves are:

- It is a wave in severe sea (because “freak” wave in a weak sea is out of interests)
- Limitations on the wave height: e.g. $h \geq 2.4 h_s$ .
- Limitations on the crest height: $c \geq 0.65h$ .
- Limitations on the wave position (small waves before and after a freak wave).

A part of wave record with a freak wave and generalized form is shown on the fig.2.

Hence freak wave is a random impulse in the sea surface with prescribed feature, summarized in the table 1. What are the reasons of freak wave generation?

Fig. 1. Regions of possible arising of freak waves (from [4]).

Table 1. Some definitions of freak (rogue) waves

| # | Source | Criteria | |
|---|---|---|---|
| | | **Statistical sample parameters** | **Individual wave parameters** |
| **1** | WMO, 1975 [9] | — | high wave with the deep trough |
| **2** | Faulkner, 2000 [10] | $h/h_s \geq 2.4$ | — |
| **3** | Kimura and Ohta 1992 [11] | — | $h>2h^-, h>2h^+, c>0.65h$ |
| **4** | Wolfram et al, 2000 [12] | $h/h_s \geq 2.3$ | $\delta=(gT^2/2\pi h_s)>0.5$ |
| **5** | Kjeldsen, 2000 [4] | $\max c > 4\sqrt{m_0}$ | $\max c^- < 4\sqrt{m_0}$, $\max c^+ < 4\sqrt{m_0}$<br>$\mu=(c/h)\approx 0.7$<br>$\Lambda=(L''/L')>2.0$<br>$\varepsilon=c/L'$ |

*Comments: $h_s$ –significant wave height, c-wave crest, $h^-$, $h^+$ - wave height before and after a freak wave, $\mu$ - horizontal asymmetry parameter, $\Lambda$ - vertical asymmetry factor, $\varepsilon$ - crest front steepness.*

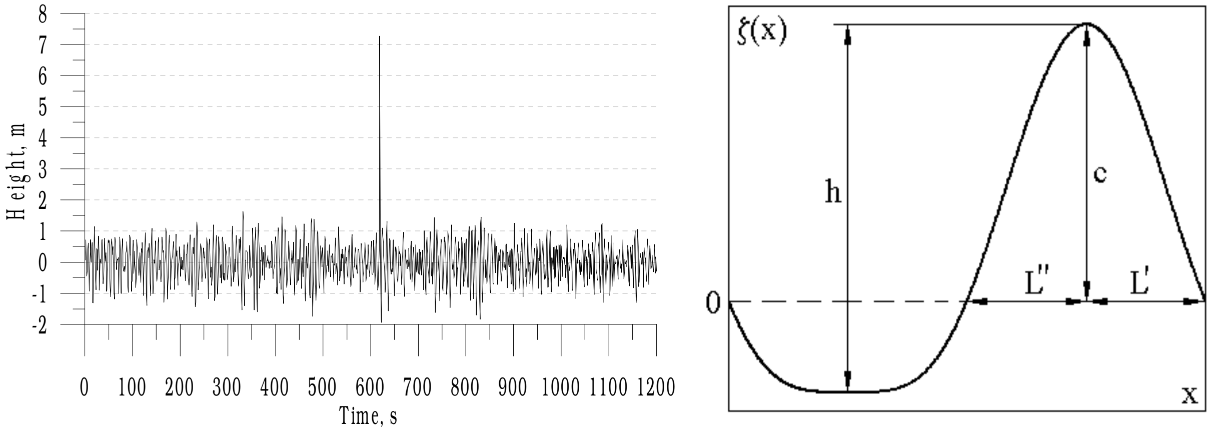


Fig. 2. Example of freak wave. Part of wave record in NE part of Black sea (due to kindness of *B. Divinsky*) in the *left*, and its parameterization (in the *right*).

## 3. MAIN REASONS OF FREAK WAVE GENERATION

All the reasons may be divided into external and internal, they are generalized in the table 2. It is follows, that internal reasons are connected with dispersion of wind wave propagation (dependence of phase velocity from frequency). The external - are metocean reasons, bottom topography and similar. In particularly for SE cost of Africa the following factors are the main [5]:

- Submarine topography, (continental shelf narrows abruptly);
- The Agulhas current (max velocity 4-5 knots. The width 60-100 n. miles);
- Strong winter W, SW winds after the passage of the cold front;
- Combination of locally generated waves and those coming from the Southern ocean.

Summarizing internal and external reason it is follows, that there are a range of different physical mechanisms:

- Phase combination of components;
- Steepness-induced crest increase ("Stokes effects");
- Nonlinear self focusing;
- Multi-directional effects;
- Bottom effects (finite depth, refraction);
- Current effects;
- Wind influence;
- Storm age and duration

Anyway freak wave is always high (extreme) wave, which is dangerous to ships or drilling units. What are the main approaches to extreme wave estimation?

Table 2. Main reasons of freak wave generation

| External | Internal |
|---|---|
| • Wave and opposing current interaction;<br>• Focused wave groups and their interaction;<br>• Refraction around shoals or from inclined sea beds;<br>• Wave caustics from diffraction at coastlines and around islands;<br>• Young waves are steep; especially in intensifying winds.<br>• Crossing wave systems and (or) opposing wave trans.<br>[10] | • Frequency modulation in random sea [14].<br>• Variable met. conditions generated the frequency modulated wind wave packets. Frequency modulation leads to larger amplification of the freak waves than the amplitude modulation [15].<br>• Cooperative effect of four- and five-wave interactions [16].<br>• The high-order nonlinearties more than third order [17]<br>• Temporal-spatial focusing. Nonlinear focusing (BF instability).<br>• The phasing and direction of freely propagating wave components is such, that large number of waves crest arise at one point. Directionality of a wave field play a crucial role. Large ocean waves occur as isolated events [18]. |
| An inherent energy fluctuation with a period much lager than 20 minutes. [13]. | |

## 4. EXTREMES OF WAVE HEIGHTS IN A POINT AND SPACE

There are a lot of approaches to calculations of extreme wave heights. The main are IDM (Initial Distribution Method), AMS (Annual Maxima Series), POT (Peak Over Threshold) and BOLIVAR. Their advantages and disadvantages are investigated elsewhere [2]. Short resume with the example for one region of the Mediterranean is presented in the fig 3 and explained below. Comparison of various approaches for estimation of wave heights is shown in the table 3.

IDM method estimates the extreme wave height $h_{max}$ of certain return period as quantile $h_p$ of wave height distribution F(h) with probability p (see fig. 3(a)). For log-normal long-term wave height distribution, the quantile with probability p can be computed as follows:

$$h_p = h_{0.5}\, exp\left(\frac{U_p}{s}\right). \tag{1}$$

$U_p$ is quantile of the standard normal distribution. Here quantile $h_p$ should be understood as wave height, which is likely to be observed once (at the standard synoptic observation times) in T years. In applied studies the period $T$ is called "return period", and the corresponding probability is defined as

$$p = \frac{\Delta t}{24 \cdot 365 \cdot T}\,. \tag{2}$$

Where $\Delta t$ is interval (in hours) between subsequent observations (say, 6 hours). Then we get $p = 0.000684/T$. For $\Delta t = 3(hr)$, we get $p=0.000342/T$.

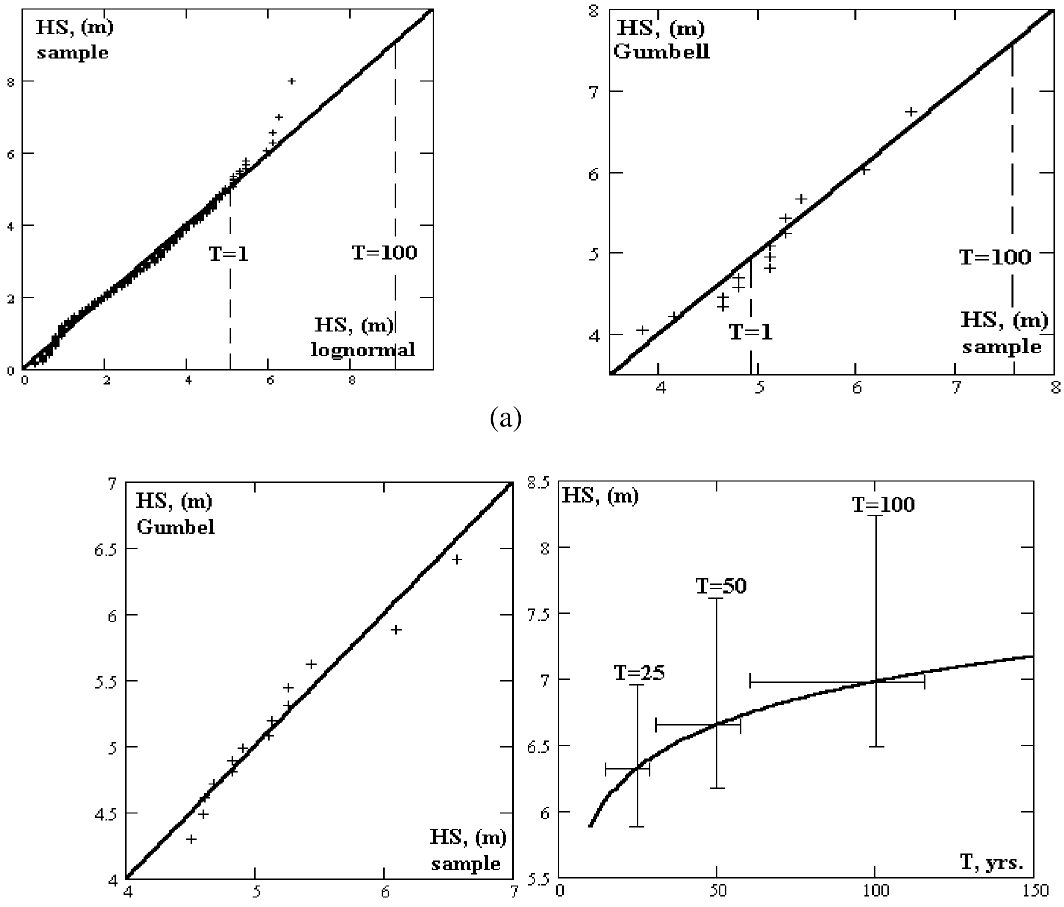
AMS approach defines $h_{max}$ as the last term of the ranked independent series of wave heights h (see fig 3(b)). Thus it is a random value with Gumbel distribution

$$F(x) = exp(-exp(-a(x-b))). \qquad (3)$$

Where a, b – parameters.

In the POT approach the k strongest storms with the heights greater than selected threshold. (In the fig 3(c), threshold is 4.5m). Thus, the POT method estimates depend on the choice of threshold and approximations for corresponding distributions. Unlike other methods, in the POT approach the uncertainty is connected both with the wave height $h_p^*$ and return period. For example, the 25-year wave height estimate in fig. 3 (d) is found to be in the range of 7.2 – 8.4 (m), and return period is in the range of 20-45 years.

BOLIVAR approach considered *n* samples, consisting of heights $h^{+}_{ij}$ of the largest waves in the *k* the strongest storms in year number *i*,(i=1,..,n; j=1,…,k) BOLIVAR approach exclude the limitations of the POT method and take into account the asymptotic characteristics of AMS. For the computations of extremes by means BOLIVAR the multiscale model of wind waves variability are required [2].



(a) (b)

(ñ) (d)

Fig.3. Distribution of significant wave height HS (m). IDM approach (a), AMS (b), POT (c,d). NW Mediterranean, 1969–1984.

Table 3. Values of extreme wave heights, calculated by various approaches. NW Mediterranean.

| **Approach** | **1year** | **10 years** | **25 years** | **50 years** | **100 years** |
|---|---|---|---|---|---|
| *IDM* | 5.2 | 7.0 | 7.8 | 8.5 | 9.1 |
| *AMS* | 4.8 | 6.0 | 6.6 | 7.1 | 7.6 |
| *POT* | 5.5 | 5.9 | 6.3 | 6.7 | 7.0 |
| *BOLIVAR 1st maxima* | 4.8 | 6.0 | — | 7.1 | 7.6 |
| *BOLIVAR 2nd maxima* | 3.8 | 4.8 | — | 5.5 | 5.8 |
| *BOLIVAR 3rd maxima* | 3.4 | 4.2 | — | 4.7 | 4.9 |

Table 4.Main parameters of a storm

| **Description** | **Notation** | **Definition** |
|---|---|---|
| *Area* | $S_\Omega(t)$ | $\int_{\Omega(t)} d\mathbf{r}$ |
| *Equivalent diameter* | $L(t)$ | $2\sqrt{S_\Omega(t)/\pi}$ |
| *Averaging wave height* | $\bar{h}(t)$ | $\int_{\Omega(t)} h(\mathbf{r},t)d\mathbf{r} \Big/ S_\Omega(t)$ |
| *Geometric centre (“centre of gravity”)* | $\mathbf{r}_0(t)$ | $\int_\Omega h(\mathbf{r},t)\mathbf{r}d\mathbf{r} \Big/ \int_\Omega h(\mathbf{r},t)d\mathbf{r}$ |
| *Maximum wave height* | $h^+(t)$ | $\max_{\mathbf{r}\in\Omega(t)}\left[h(\mathbf{r},t)\right]$ |
| *Location of the maximal wave height* | $\mathbf{r}^+(t)$ | $\left\{\mathbf{r} : h(\mathbf{r},t) = h^+(t)\right\}$ |

The AMS method has the most solid theoretical foundation. The BOLIVAR method represents its further development that includes into consideration the second, third and, potentially, other maximums in a year. Each of the considered methods has its advantages and disadvantages and has to be used accordingly.

For navigation and shipbuilding it is important to examine extremes not only in a single point of a basin, but in some area, in general, in the all sea. Then, by storm it is meant spatiotemporal domain

$$\Omega(t) = \{\rho : \quad h(\rho,t) > z\} \tag{4}$$

where $z$ is the level of the storm and additional parameters are defined in Table 4.

Duration $\Im$ of each storm, for selected threshold $z$, is defined as number of synoptic terms, when condition (4) is valid. Time duration between storms is weather window $\Theta$. Storm intensity may be determined by different ways (square $S_\Omega$ of space Ω, it energy conditions, etc). Here we characterize storm intensity by its maximum wave height:

$$h^+(t) = \max_{\Omega(t)}\left[h(\rho,t), t \in \Im\right]. \tag{5}$$

A system of three random values $\{ h^+, \Im, S_\Omega, \Theta \}$ reveal main feature of synoptic variability of waves due to moving and development of pressure fields over the sea.

Storm evolution in any basin may be presented as an impulse random field

$$\zeta(\rho,t) = \sum_k W_k^{z(\rho)}(\rho,t \mid X). \tag{6}$$

Where $W_k^{z(\vec{r})}(\bullet)$ – spatiotemporal impulse with respect level $z(\vec{r})$. At any time $W_k^{z(\vec{r})}(\bullet)$ can be presented as an elliptic cone.

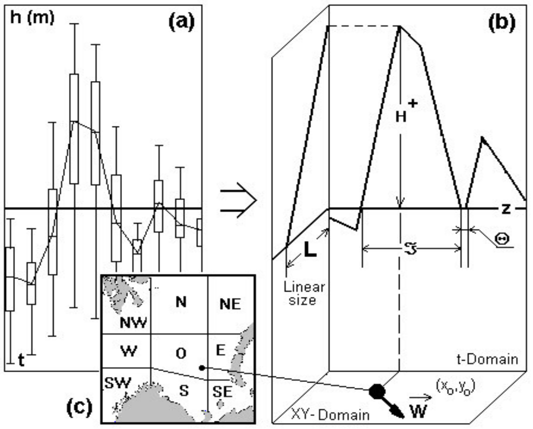


Fig. 4. The spatiotemporal parameterization of storm variability.
*(a) – representation of spatial distribution of wave heights, (b) – spatiotemporal impulse parameterization, (c) – spatial localization of the storms.*

Let us consider a storm $\{r_0(t), h^+(t), S_\Omega(t)\}$. The size of the storm area is equal to the fraction of total area of the region, where wave heights larger than z. Parameterize of storm in a space impulses in terms generalizes the BOLIVAR approach [2] from time series to spatio-temporal fields.

The behaviour of the extreme wave in a single storm in a fixed point is known [19]. For spatial region this problem more complex, because unique enumeration available only for two-dimensional waves. In the simplest case, with a narrow angular spreading of sea waves, the generalized distribution of maximal wave in a spatial storm region is

$$F_m(h) = exp\left[2\pi\int_0^L\left(-exp\left(-\frac{\pi}{4}\left(\frac{h}{\bar{h}(r)}\right)^2\right)\right)\frac{rdr}{\lambda(r)}\right] \quad (7)$$

Here 2L is the equivalent diameter of the storm, where $L = 2\sqrt{S_\Omega(t)/\pi}$, $S_\Omega(t) = \int_{\Omega(t)} d\mathbf{r}$. For small-amplitude waves $\lambda(r) \approx 36\bar{h}(r)$. The storm impulse $\bar{h}(r)$ is approximated by expression $\bar{h}(r) = h^+ - (h^+ - z)(r/L)^m$, where m is the shape parameter of storm impulse (m=1 – cone, m=2 – parabolic etc).

## 5. FREAK WAVES AS THE MULTIVARIATE RARE EVENTS

Estimation of extreme wave in spatial domain is complicated. But for moving objects (particularly, for ships) it is still recommended follow this approach. Freak wave must have a lot of specific features (see table 1). Therefore, it estimation is more complicated, than extreme wave.

Freak wave is very rare event, and procedures of statistical analysis and synthesis of huge data samples are complicated too. Moreover, due to multiscale and spatiotemporal variability of sea waves, the numerical simulation is very resource-consuming procedure. It requires the development of special approach for stochastic simulation, that allows to investigate freak waves occurrence efficiently and precisely.

There are two ways to formulate the conditions of freak waves generation in the Ocean. The first one considers the arising of the different external conditions, leading to possibility of freak wave generation. In this case computation of a joint probability of these conditions (e.g. combinations the severe waves and opposite currents etc.) is needed. But the real input of this approach is not obvious, because it is hard to take into account all the driving factors. Another way considers the ensemble of all waves (their heights *h*, periods $\tau$, crests *c* etc.) and estimate occurrence of its crucial combinations, leads to freak wave arising. This approach seems more reliable in practice, because it is based on the consideration of freak waves as the elements of the same ensemble, as all the waves. But, it requires the sophisticated statistical techniques for rare events analysis, because the extreme combinations of the waves parameters belong to the tails of its joint probability function.

Some definitions of freak waves as set of parameters $\Xi = \{h, \tau, c, ...\}$, characterizing the shape of the wave, is presented in the table 1.

All the formulated criteria of freak wave may be considered in terms of associated multivariate quantile curve $\Xi(p)$ of the joint distribution

$$P_{\Xi}(h_s, h, c, L', L'', ...) = \\ P(h_s)P(h \mid h_s)P(c \mid h, h_s)P(L' \mid c, h, h_s)... \quad (8)$$

The elements of product in the right part of Eqn. (8) corresponds to elementary scenarios, defined the necessary conditions for freak wave arising. But only whole set describes the real risk of the freak wave occurrence. This way allows formulating the scenarios of freak wave generation step-by-step, consequently. The principal scheme of these scenarios is shown in the fig. 5.

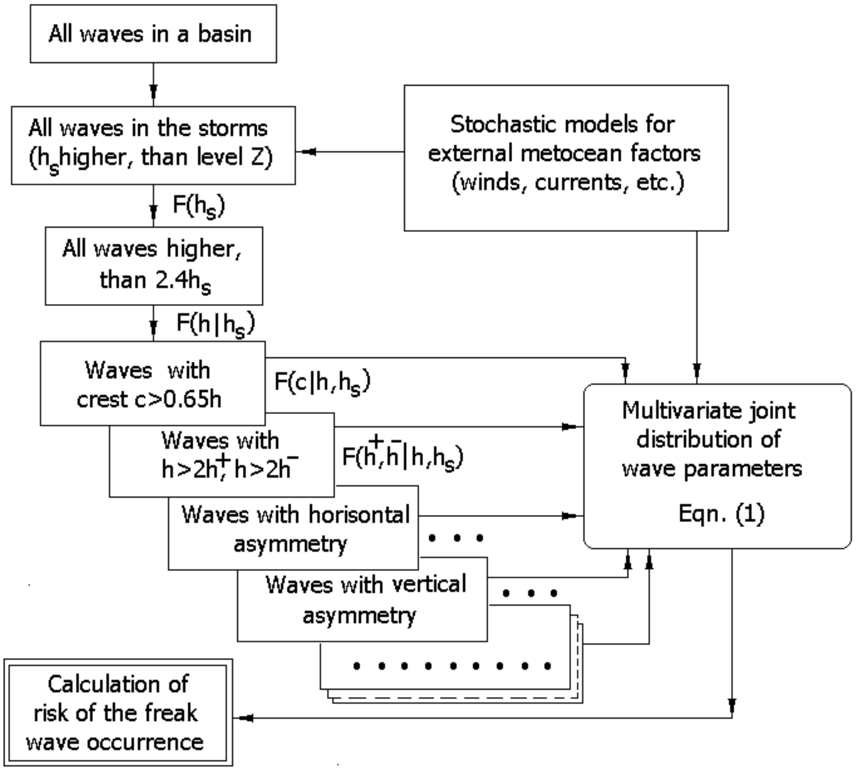


Fig. 5. General scheme of freak wave generation scenarios

## 6. APPLICATION TO RISK ANALYSIS

The problem of extreme and freak waves estimation is associated with the formal safety analysis (FSA) of the ocean vehicles (e.g. fishing vessels etc.). The one of the most perspective approaches for dealing of certain aspects of the safety in the ocean is the risk analysis (RA) [20]. It usually reveals some problems of the optimal design and driving of the ocean vehicles, on the base of exploration of some features of variability of the environmental events and the correspondent objects' responses. In accordance with the paper [21], let us consider below the three basic stages of RA.

***Risk identification*** highlights the hierarchy of the events, associated with the danger for the vehicle. For example, for the vessel capsizing (loss of the stability) in a sea, one of the leading factors may be the rough weather conditions (storm waves, wind squalls etc.). Moreover, the crucial influence of the sea waves may be considered dually:

<u>Ordinary extreme waves:</u> as the impact to external excitation, leads to dangerous rolling amplitudes.

<u>Freak (steep and breaking)</u> waves: as the impact to external influence, leads to arising of free water on the deck, and also, the decreasing of GM.

Really, these reasons are coherent, because formally the capsizing may be a result not of a freak wave, but due to loads of the ordinary waves on the vessel with the water on the deck just after the freak wave breaking.
RA as the dangerous environmental events for a vehicle may be presented as the *tree of the risks* [21]. The scheme in the fig. 5 may be treated also as the example of tree of the risks for the freak waves arising.

***Quantitative risk estimation*** is the next stage, based on the developed tree of risks. It allows to estimate the total probability $p_i$ of the crucial situations $i$ for each branch of the tree. In accordance with the Eqn. (8) [22]:

$$p_i = \sum_j q\left(C_i \mid W_j\right) q(W_j), \qquad (9)$$

where $q(W_j)$ is the probability of the environmental conditions $W$ (e.g., calms, rough sea, extreme of freak waves), and $q(C_i \mid W_j)$ – the conditional probability of the characteristics of the ship response Ñ (e.g., extreme roll amplitudes etc.).

The way for the estimation of the $q(W_j)$ is briefly considered in the previous part of this paper. The calculation of the $q(C_i \mid W_j)$ requires sophisticated methods for simulation of the extreme behavior of the ship on the waves, e.g. [23].

Sometimes only the order of the probability value may be correctly computed. For example, for the small fishing vessel (L=27 (m), B=5,1 (m), T=2,2 (m)) the probability of capsize in the NE part of Black sea (where the freak waves from Fig. 1 were observed) is $\sim 10^{-4}$ per year for the ordinary extreme wave conditions. But the probability to loss stability due to impact of freak wave is $\sim 10^{-6}$ per year.

***Choosing of the optimal strategy.*** It is seems, that the real input of the freak waves branch in the RA is rather low in comparison with ordinary high waves. But the main importance in the RA paid not only to the probability value, but to the values of associated losses also.

For example, let us consider the branches of the risk tree, correspondent to different weather conditions. E.g., for small fishing vessel in NE part of the Black sea the following classes of weather may be considered.

$A_1$ (88%) – waves in the calms;
$A_2$ (11%) – rough waves;
$A_3$ (0.9%) – extreme rough waves;
$A_4$ (0.1%) – conditions, when a freak wave may arise.

The state $A_1$ is associated with the normal operational conditions, the state $A_2$ – operations with possible losses of the benefits, and $A_3$, $A_4$ – dangerous states with huge material losses (damaging and destroying of the equipment and the vessel). For the fixed conditions $A_i$ the activities (strategies) of the shipmaster leads to certain benefits (or losses). E.g., we may consider three general strategies of the shipmaster behavior

$B_1$ – «adventure»;
$B_2$ – «neutral»;
$B_3$ – «insurance».

The loss function $L(A_i,B_j)$ is associated with the each couple $(A_i,B_j)$. It defines the losses $(L<0)$ or the benefits $(L>0)$ as the result of the strategy $B_j$ for the weather conditions $A_i$. For the above mentioned example this function became the matrix:

$$L = \begin{array}{c} \begin{array}{ccc} B_1 & B_2 & B_3 \end{array} \\ \left[\begin{array}{ccc} 1.5 & 0.7 & 0.5 \\ -1 & 1 & 0.8 \\ -10 & -1 & 0.5 \\ -10 & -10 & -10 \end{array}\right] \end{array} \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{array} . \tag{10}$$

Here the values on the diagonal corresponds to the normal conditions of the operations (some normal benefits). The values of the benefits above the diagonal is less then 1 (due additional expenses to safety). Below the diagonal the benefits are negative (due to losses of equipment, or ship damaging). All the elements of (10) are computed in the second stage (as the identification of risks for each branch).

It is seen, that in the Eqn. (10) all the values of the loss in the line $A_4$ are (–10). It reflects the fact, that today the freak wave prediction is impossible, and the shipmaster has no possibility to avoid this incident.
In accordance with Eqn. (9) the expected losses (risk) for the fixed strategy $B_j$ is expressed as:

$$R(B_j) = \sum_k L(B_j, A_k)\, p(A_k) \tag{9}$$

For considering example, the "neutral" strategy $B_2$ is the most beneficial ($R(B_2)=0.65$) For other strategies $R(B_1)=0.23$ and $R(B_3)=0.45$.

Note, that in the matrix (10) another causes of the risks are not regarded. In general case the elements of (10) are the deterministic functions of both the time and probabilistic characteristics of the wind and waves.

## 7. CONCLUSIONS

The proposed technique allows to estimate the probability of the extreme and freak (abnormal) waves arising, in accordance with criteria from Table 1. Probability of extreme wave in a point and in a whole basin are different and needs special approach, proposed in section 4. Freak wave, determined only by one criterion is not rare event. For example, in the Central part of Barents Sea the storms above 2.0 (m) occur in 32% cases, and above 4.0 (m) - in 12%. For two-dimensional wave surface 1,3% of storms has a freak wave ($h \geq 2.4 h_s$). For three-dimensional wave surface: in all the storms (above 2.0 (m)) it may arise from 2 to 45 freak waves (with 90% probability), and in mean – 12 waves. Moreover, for 4% of storms the waves with $h \geq 3.0 h_s$ occurs.
The consideration of a freak wave occurrence is needed for FSA of ocean vehicles.

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