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Wave height statistics for seakeeping assessment of ships in the Adriatic Sea

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ABSTRACT

The paper presents methodology and results of the development of sea states statistics for the Adriatic Sea. Such statistics is still lacking despite a need of the shipping industry. The presented study is based on the Atlas of Climatology containing statistics of sea states observations in the Adriatic Sea made by merchant ships during the period of 15 years. The results, presented in the Atlas in the form of "wave roses", are digitalized and empirical frequencies of sea state occurrences are obtained. The 3-parametric Weibull distribution is then fitted through empirical data points enabling the "smoothening" of the histogram. The resulting histogram is compared with other studies for the long-term prediction of the sea states in the Adriatic Sea. The paper concludes with the discussion on the accuracy and applicability of the results.

1. Introduction

The aim of the present study is to develop the statistics of the sea states in the Adriatic Sea, which is a rather closed and elongated sea basin about 800 km in length and 200 km in breadth, connected to the Mediterranean Sea by the relatively narrow Strait of Otranto, Fig. 1. The motivation for the study is that the occurrence probability of different wave conditions in the Adriatic Sea is still not readily available despite the fact that the wave data are useful for the industry, researchers and public authorities.

The seakeeping calculation for the structural reliability assessment of a damaged oil tanker in the Adriatic Sea is the primary application area of the wave statistics developed in the present paper. The safety assessment of oil tankers in the Adriatic Sea is nowadays a concern of the whole public community. In such a closed sea basin, with relatively low activity of sea currents and waves, serious oil pollution due to a major oil tanker accident would cause almost irreversible environmental disaster and enormous economic losses. The amount of oil transported across the Adriatic Sea nowadays amounts to some 85–100 millions of tons per year with a significant growing tendency. For indication, the oil traffic in the Adriatic Sea is increasing for about 10% in the period of every six years. Although more than 80% of the oil is presently transported through Italian ports Venice and Trieste, the Croatian oil terminal Omišalj in the North Adriatic Sea is, because of its favorable geographical location, becoming very attractive for the transfer of the Russian oil. Therefore, it is expected that the oil transport through the Adriatic Sea will continue to increase considerably in the following years. The study of wave loads on oil tankers in the Adriatic Sea presented by Parunov and Senjanović (2005) showed that the probability of a structural failure of an intact oil tanker due to purely environmental loads was almost negligible. However, the structural failure may occur due to ship collision, grounding or some other type of human mistake. The probability of such an accident is unavoidably increasing with the number of ships involved in the transport. In case of such an accident, the ship strength could be considerably reduced making wave loads important for the structural safety assessment (Luis et al., 2009). To perform a realistic analysis of such a scenario, the reliable wave statistics is a necessary prerequisite.

The seakeeping performance for safety or comfort assessment of RO-RO ships, ferries and small ships operating in the Adriatic Sea requires very often a probabilistic description of the sea environment. The prime example is the application of the Directive 2003/25/EC of the European Parliament and of the Council of 14 April 2003 on specific stability requirements for RO-RO passenger ships. The directive requires refined and reliable probabilistic description of the sea states in coastal seas in order to decide if a retrofitting of the existing ships would be required. Since the retrofitting is generally quite expensive, it is very useful to develop a histogram of the sea states for both safety and economic reasons.

The statistics of occurrence of different sea states used in the paper is provided by the Hydrographic Institute of Republic of Croatia (1979). The data are collected by observations from merchant ships making them suitable for application on the analysis of seagoing ships. Observations, although performed a couple of decades ago, have still not been used for deriving the histogram of the sea states.

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Fig. 1. The Adriatic Sea.
Source: hr.wikipedia.org.

The state-of-the-art of wave atlases in the Adriatic Sea is represented by MEDATLAS (Cavaleri, 2005) and WORLDWAVES (Barstow et al., 2003). The former atlas is the result of the project sponsored by the Italian, French and Greek Navies, resulting in the extensive atlas of the wind and wave conditions in the Mediterranean Sea. The MEDATLAS is based on the information derived from the archive of the European Center for Medium—Range Weather Forecasts, UK, then calibrated on the basis of the data available from the ERS1-2 and Topex satellites. The WORLDWAVES database contains data calibrated using different satellite missions, in-situ measurements and wave model simulations. A grid with about 40 calibration points is available for the Adriatic Sea within WORLDWAVES.

The present paper is organized in a way that a general description of characteristic wind patterns in the Adriatic Sea is firstly provided. In the next sections, wave data used in the present study are described in more details followed by the method employed for their probabilistic treatment. Methods used for long-term prediction of significant wave heights and individual wave amplitudes follow basic work of Ochi (1978). A comparison with some other available long-term predictions in the Adriatic Sea is made and the accuracy of the results is discussed. The paper ends with appropriate conclusions and recommendations.

2. Environmental conditions in the Adriatic Sea

The Adriatic Sea is elongated over the southeast to the northwest direction and has a roughly shallow elliptical shape, Fig. 1. Two main patterns of winds in that area are bora and sirocco. The bora is a strong, gusty and cold wind which blows from the northeast (NE) quadrant and is mostly pronounced in the northern part of the Adriatic Sea. The sirocco blows along the whole Adriatic Sea, predominantly from the south (S) and southeast (SE) quadrants, mainly with moderate and strong force. The bora and sirocco blow with gale force in average three times a year with a persistence between 1 and 17 h.

The wave heights developing in the Adriatic Sea are limited both by the wind duration and fetch. In the case of bora, which blows parallel to the shorter side of the fictitious rectangle representing the Adriatic Sea, fetch is clearly the predominant limiting factor and because of the rather violent speeds that the bora may have, steep but not very high waves are developed. The sirocco is a more persistent wind comparing to the bora, it blows along the longer side of the Adriatic Sea where fetch is much larger, while the maximum gust speed of sirocco is lower comparing to the bora. Consequently, the sirocco tends to generate higher and less steep waves than the bora.

3. Description of wave observations

The frequencies of occurrences of sea states of different severities for the Adriatic Sea used in the present paper are collected from the meteorological observations taken by merchant and research ships from 1957 till 1971 with a total of 43,274 complete ship meteorological observations. Observations are published in the Climatology Atlas by the Hydrographic Institute of Republic of Croatia (1979). The meteorological data are grouped into wave zones represented by "squares" having lengths of sides equal to 1° of latitude and longitude, Fig. 2. The Climatology Atlas contains monthly averages of frequencies of wave directions and heights together with maximum observed wave heights for each wave direction.

The data in the Atlas are presented in the form of "wave roses" for each month and for each wave zone. A typical "wave rose" (wave area No. 17 in January) is presented in Fig. 3. The number in the corner of each zone represents the total number of wave observations in a particular zone, while the number in the circle in the center of each "rose" represents the percentage of the calm seas (waves so small that could not be measured). The upper numbers on each of the bars represents the average significant wave height observed from a particular direction, while the lower

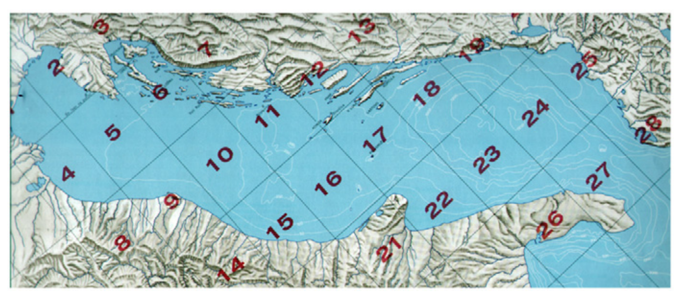

Fig. 2. Division of the Adriatic Sea in wave zones.

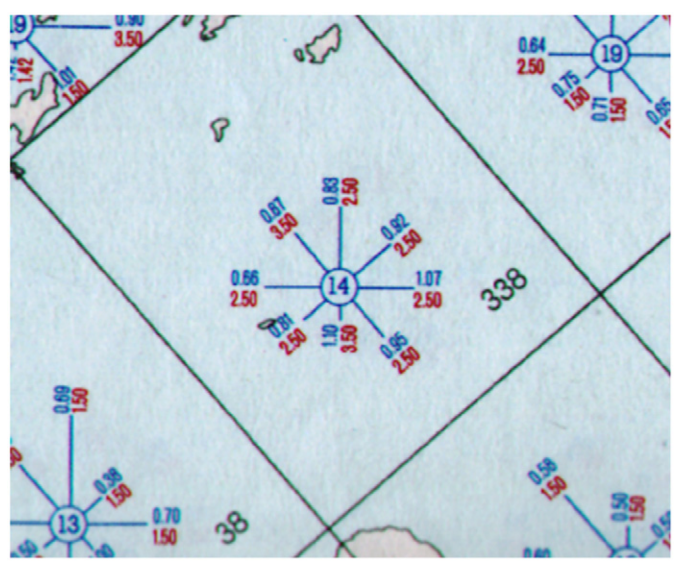

Fig. 3. Typical "wave rose" (Area 17 in January).

number denotes the maximum significant wave height ever observed from that direction. The length of the bar in each of the zones represents the relative frequency of waves coming from the direction of the bar with respect to all directions.

4. Statistics of sea states

In the present paper, results from the Climatology Atlas are used in the following way:

- the data given in a form of wave roses are digitalized;
- a representative shipping route in the Adriatic Sea is assumed;
- the digitalized wave data from different wave zones are combined for a representative shipping route;
- the 3-parameter Weibull probability distribution is fitted to the data for the representative shipping route;
- based on the 3-parameter Weibull distribution, the “smoothed” histogram of the occurrences of sea states is created.

Digitalization of data is performed in a way that readings from the “wave roses” are sorted into intervals from 0 to 5 m, with a step of 0.5 m. Therefore, the mean values of the intervals are 0.25, 0.75, …, 4.75 m. For each wave zone and wave direction, the number of the sea state is calculated and that number is set in the interval corresponding to the mean value from the “wave rose”. The maximum ever observed value denoted in the “rose” is assumed to have occurred only once and is put in the corresponding interval. Digitalized values for the “wave rose” from Fig. 2 are presented in Table 1.

For each wave zone, the data presented for each month are averaged on the annual basis. The annual average values of frequencies of occurrences for wave zone No. 17 are presented in Table 2.

The representative shipping route for an oil tanker in the Adriatic Sea is assumed to pass through zones 5, 10, 11, 16, 17, 18, 22, 23, 24 and 27 from Fig. 2. Thus, the unique frequencies of occurrence of the sea states, representing shipping route in the Adriatic Sea, are determined and presented in Table 3.

5. Probabilistic description of sea states occurrences

In order to get a smooth histogram of sea state occurrences and to be able to predict extreme seas states with a very low probability of exceeding, the theoretical probability distribution is fitted to the observed data. The 3-parameter Weibull distribution is usually used for the probabilistic description of sea states in long term periods. The 3-parameter Weibull distribution is given as

$$F(H_S)=P(\hat{H}_S<H_S)=1-e^{-\left(\frac{\hat{H}_S-\varepsilon}{\theta}\right)^{\alpha}},\quad H_S,\hat{H}_S\geq\varepsilon \tag{1}$$

where ε is the location parameter, θ is the scale parameter and α is the shape parameter. Location parameter ε has an important physical meaning as a small significant wave height always present that represents permanent sea activity (Sarpkaya and Isaacson, 1981). $P(\hat{H}_S<H_S)$ represents the probability that the random variable significant wave height $\hat{H}_S$ takes a value lower than certain H_S.

Table 2
Annual average frequencies of sea state occurrences for the wave zone No. 17.

Class i	Interval m	Mean value m	No. of sea states
1	4.5–5	4.75	0
2	4–4.5	4.25	1
3	3.5–4	3.75	1
4	3–3.5	3.25	2
5	2.5–3	2.75	3
6	2–2.5	2.25	4
7	1.5–2	1.75	49
8	1–1.5	1.25	341
9	0.5–1	0.75	3406
10	0–0.5	0.25	1435
			$\Sigma=5242$

Table 3
Frequencies of occurrence of sea states for representative shipping route in the Adriatic Sea.

Class i	Interval m	Mean value m	No. of sea states
1	4.5–5	4.75	0
2	4–4.5	4.25	7
3	3.5–4	3.75	7
4	3–3.5	3.25	27
5	2.5–3	2.75	34
6	2–2.5	2.25	63
7	1.5–2	1.75	304
8	1–1.5	1.25	3972
9	0.5–1	0.75	19,954
10	0–0.5	0.25	8806
			$\Sigma=33{,}172$

Table 1
Frequencies of sea states occurrences for the “wave rose” from Fig. 3.

Area	17
Month	1 (January)
Percentage of the calm seas	14
No. of wave observations	338

Direction of waves	Mean value m	Max value m	Frequency %	No. of sea states	Class i	Interval m	No. of sea states
NE	0.83	2.5	14	47	1	4.5–5	0
E	0.92	2.5	10	34	2	4–4.5	0
SE	1.07	2.5	13	44	3	3.5–4	0
S	0.95	2.5	12	41	4	3–3.5	1
SW	1.1	3.5	4	14	5	2.5–3	0
W	0.81	2.5	8	27	6	2–2.5	7
NW	0.66	2.5	13	44	7	1.5–2	0
N	0.87	3.5	12	41	8	1–1.5	56
			$\Sigma=86$	$\Sigma=291$	9	0.5–1	227
					10	0–0.5	47
							$\Sigma=338$

The probability of H_S being exceeded is then given as

$$Q(H_S) = 1 - P(H_S) \tag{2}$$

For each value $H_{S,i}$ from Table 3, the empirical exceedance probability is given by the Weibull expression (Chow, 1964)

$$Q(H_{S,i}) = \frac{\sum_{j=1}^{i} f_j}{N+1} \tag{3}$$

where $\sum_{j=1}^{i} f_j$ represents the cumulative frequency of all values larger than or equal to $H_{S,i}$. N appearing in Eq. (3) represents the total number of observations. The empirical probability $P(H_{S,i})$ that $H_{S,i}$ is not exceeded is then given by Eq. (2).

To present the Weibull distribution in linear scale, Eq. (1) should be logarithmed twice. Then, it takes the following form:

$$\ln(-1 \cdot \ln(1 - F(H_S))) = \alpha \ln(H_S - \varepsilon) - \alpha \ln \theta \tag{4}$$

Therefore, the 3-parameter Weibull distribution may be represented as a straight line if on the abscissa axis values $\ln(H_S - \varepsilon)$ are set, while on the ordinate axis values representing left hand side of Eq. (4) are given. Parameters of the straight line (slope a and interception b) can be determined by the least squares method. The Weibull parameters are then calculated as

$$\alpha = a, \quad \theta = e^{-(b/\alpha)} \tag{5}$$

Since the location parameter ε is unknown, it should be determined before fitting of the straight line. That could be accomplished by the non-linear optimization method, with the objective function defined in a way to minimize the discrepancy between the discrete points and the fitted straight line (Mansour and Priston, 1995). However, in the present paper an efficient direct method of fitting the 3-P Weibull distribution presented by Rao (1992), has been employed.

The first step of the fitting method is to assume $\varepsilon = 0$, corresponding to the 2-parameter Weibull distribution. The empirical data points to be fitted are firstly presented in diagram $[\ln H_S, \ln(-\ln(1 - F(H_S)))]$. An approximate curve is then fitted through data points that are generally not lying on a straight line. Such a diagram for the case of a representative shipping route in the Adriatic Sea is presented in Fig. 4.

According to the procedure proposed by Rao (1992), three points on the curve are to be selected such that ordinates of the points are equally spaced (e.g. points 1, 2 and 3). From the abscissa of those points, H_{S1}, H_{S2} and H_{S3} could be calculated readily. It is easy to show that the location parameter ε is then given as (Rao, 1992)

$$\varepsilon = \frac{H_{S1} H_{S3} - H_{S2}^2}{H_{S1} + H_{S3} - 2H_{S2}} \tag{6}$$

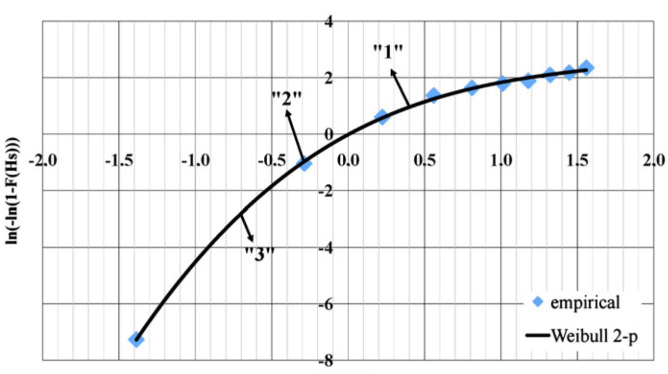

Fig. 4. Fitting of 2-parameter Weibull distribution to the empirical data points.

For points 1, 2 and 3 from Fig. 4, one finds $H_{S1} = 1.49$ m, $H_{S2} = 0.74$ m and $H_{S3} = 0.47$, respectively. From Eq. (6) it follows that $\varepsilon = 0.3325$. That enables to represent the empirical data points in the diagram with abscissa $\ln(H_S - \varepsilon)$. The points are now located approximately on the straight line that can be fitted, as represented in Fig. 5.

Thus, the theoretical probability distribution is presented in linear scale as

$$\ln(-\ln(1 - F(H_S))) = 1.015 \ln(H_S - 0.3325) + 0.8593 \tag{7}$$

The remaining parameters of the Weibull distribution are given by (5) as

$$\alpha = a = 1.015, \quad \theta = e^{-(b/\alpha)} = 0.4289 \tag{8}$$

The observed (empirical) and theoretical probability density functions are presented in Fig. 6, where good agreement can be noticed.

The theoretical distribution fitted through empirical data points enables the "smoothening" of the empirical histogram. This is presented in Fig. 7 and Table 4, where 10,000 sea states are extracted by the simulation from the theoretical probability density function. This histogram may be recommended as representative for the shipping routes in the Adriatic Sea.

The important information that may be determined from the developed histogram are the most probable significant wave heights for different return periods. The most probable values are calculated from the 3-P Weibull distribution (1) for probability level of $1/N$, where N denotes the number of sea states in

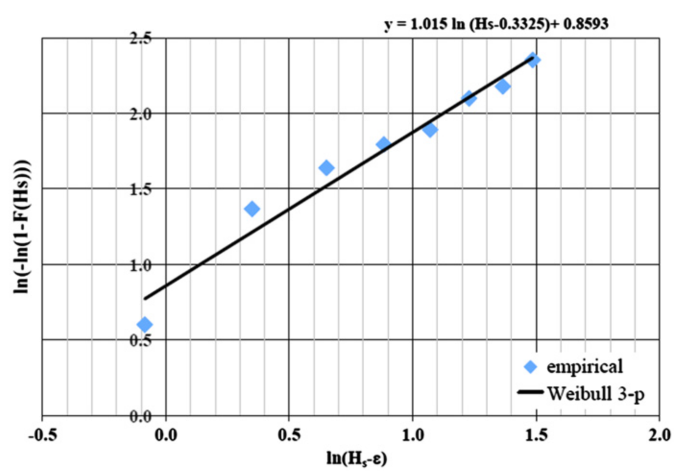

Fig. 5. Fitting of the 3-parameter Weibull distribution to the empirical data set.

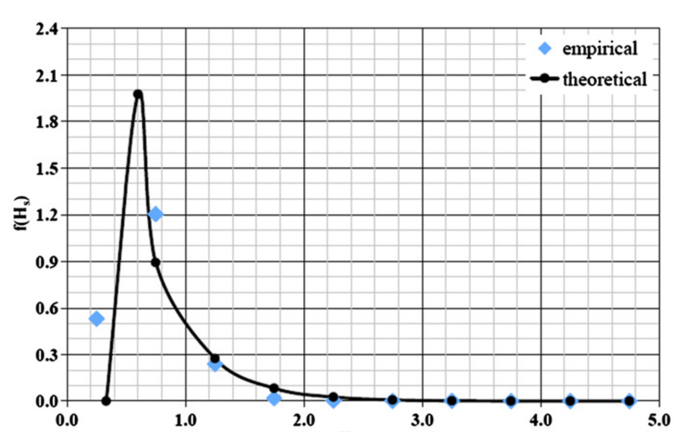

Fig. 6. Comparison of measured and theoretical probability density functions.

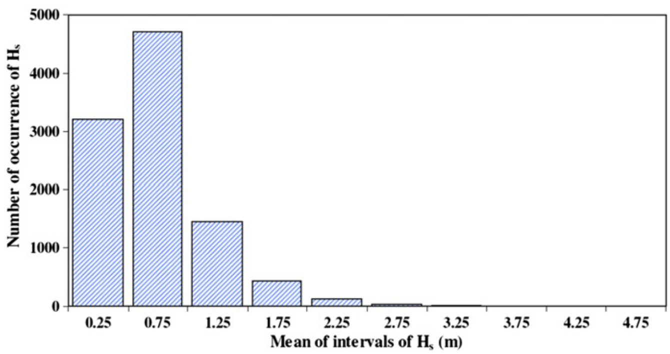

Fig. 7. Recommended histogram for representative shipping route in the Adriatic Sea.

Table 4
Recommended histogram for representative shipping route in the Adriatic Sea.

Class *i*	Interval *m*	Mean value *m*	Frequency
1	4.5–5	4.75	0
2	4–4.5	4.25	1
3	3.5–4	3.75	3
4	3–3.5	3.25	12
5	2.5–3	2.75	40
6	2–2.5	2.25	133
7	1.5–2	1.75	442
8	1–1.5	1.25	1457
9	0.5–1	0.75	4716
10	0–0.5	0.25	3196
			Σ=10,000

Table 5
The most probable extreme significant wave height for different return periods based on different assumed durations of sea states.

Return period, years	Duration of short-term sea states, hours			
	1	3	8	12
1	4.10	3.65	3.25	3.08
5	4.76	4.31	3.91	3.74
10	5.04	4.59	4.19	4.02
20	5.32	4.88	4.48	4.31
50	5.70	5.25	4.85	4.68
100	5.98	5.53	5.13	4.97

the return period. N depends on the assumed duration of individual sea states, which is usually between 1 and 12 h. The most probable extreme significant wave heights for different return periods are presented in Table 5 and Fig. 8.

6. Wave spectrum in the Adriatic Sea

The standard wind wave spectrum for the Adriatic Sea is proposed by Tabain (so called T-spectrum) (1997)

$$S_\eta(\omega) = 0.862\frac{0.0135g^2}{\omega^5}e^{[-(5.186/\omega^4 H_S^2)]}1.63^p \tag{9}$$

where

$$p = e^{[-((\omega-\omega_m)^2/2\sigma^2\omega_m^2)]}; \quad \omega_m = 0.32+\frac{1.8}{H_S+0.60}$$
$$\sigma = 0.08 \ \ za \ \ \omega \le \omega_m, \quad \sigma = 0.1 \ \ za \ \ \omega > \omega_m \tag{10}$$

T-spectrum represents a modification of the JONSWAP spectrum using shape parameter $\gamma=1.63$ as well as parameters $\sigma=0.08$ for the left side and $\sigma=0.1$ for the right side of the spectrum. The T-spectrum

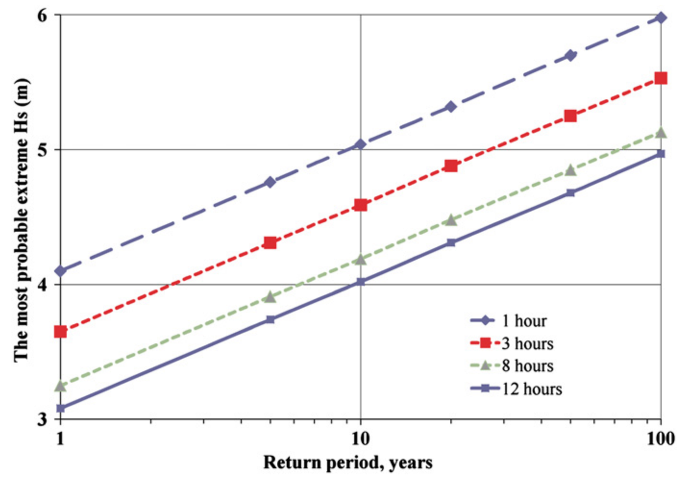

Fig. 8. The most probable extreme significant wave height for various return periods based on different assumed durations of sea states.

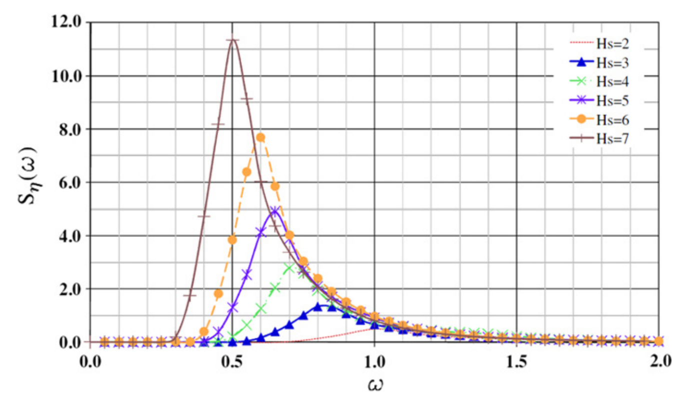

Fig. 9. Family of T-spectra.

is a one-parametric spectrum, since the functional relationship between modal circular frequency ω_m and H_S was derived for the Adriatic Sea and included in the formula. Theoretical derivation and comparison of T-spectrum with experiments is presented by Tabain (1997), where it is shown that excellent agreement with both measured and numerically hindcasted wind wave spectra for normal sea conditions is achieved. The family of T-spectra for different significant wave heights is presented in Fig. 9. T-spectrum may be recommended for seakeeping studies together with the derived histogram of sea states presented in Section 5 of the paper.

7. Long-term distribution of individual wave amplitudes

The knowledge of the wave spectra enables the computation of the long-term distribution of individual wave amplitudes $F_W(a)$. For that purpose, the well known expression is employed

$$F_W(a) = \sum_{j,k}^{n_H,n_T} F_R(a|H_S,T_Z)n_k(T_{Zk})p_{jk}(H_{Sj},T_{Zk}) \tag{11}$$

Eq. (11) $F_R(a|H_S,T_Z)$ is a Rayleigh-distributed probability of random wave amplitudes $\hat{a}$ in individual short-term sea states described by significant wave height H_S and mean zero up-crossing period T_Z. The probability is given as

$$F_R(a|H_S,T_Z) = P_R(\hat{a}|H_S,T_Z \le a|H_S,T_Z) = 1-e^{(-((a^2)/2\sigma^2))} \tag{12}$$

In case of the single-parameter T-spectrum valid for the Adriatic Sea, $p_{jk}(H_{Sj},T_{Zk})$ from (11) and (12) depends only on the significant wave height H_S. This probability is given by the newly developed wave histogram presented in Table 4. Variable $n_k(T_{Zk})$ appearing in (11) represents the ratio between the average mean zero up-crossing periods of all sea states $\overline{T}_Z$ and the mean zero up-crossing period of kth individual sea state T_{Zk}:

$$n_k(T_{Zk}) = \frac{\overline{T}_Z}{T_{Zk}} \tag{13}$$

The average mean zero up-crossing periods of all sea states is defined as

$$\overline{T}_Z = \overline{f}_Z^{-1} = \left(\sum_k^{n_T} \frac{1}{T_{Zk}} p_k(T_{Zk}) \right)^{-1} \tag{14}$$

where $\overline{f}_Z$ represents the average frequency of waves in all sea states. It is important to notice that in case of the T-spectrum, the mean periods become functions of the significant wave heights.

When the mean zero up-crossing period $\overline{T}_Z$ is defined, one may calculate the expected number of waves in the given return period T_R as

$$n = \frac{T_R}{\overline{T}_Z} \tag{15}$$

It is then convenient to fit the 2-parameter Weibull distribution to discrete values obtained by (11)

$$F_W(a) = 1 - e^{-(a/\theta)^{\alpha}} \tag{16}$$

The wave amplitude $a_{n,\max}^{\mathrm{mod}}$ satisfying the following equation:

$$F_W(a_{n,\max}^{\mathrm{mod}}) = 1 - \frac{1}{n} \tag{17}$$

is the most probable extreme wave amplitude in return period T_R.

Results of the long-term analysis are presented in Table 6.

Table 6
The most probable extreme wave amplitudes for different return periods.

Return period, years	The most probable wave amplitude, m
1	3.74
5	4.16
10	4.35
20	4.53
50	4.78
100	4.97

8. Comparison of results and discussion

In the available literature there are no similar studies for the shipping routes in the Adriatic Sea to compare the obtained results. Measurements from a fixed location are more frequent, especially in the Northern Adriatic, but the time period of continuous data collection is usually not long enough to be comparable to the presented results. An exception is the study by Cavaleri et al. (1997), describing results of 18 years of continuous wave measurement on the oceanographic tower located in the Northern Adriatic Sea, at 16 m of depth, 15 km off the coast of the Venice lagoon.

Another comparison may be done with ANEP 11 (NATO, 1983), which is a source document for specifying wind and wave conditions in the North Atlantic, Mediterranean Sea and some other coastal and landlocked areas. ANEP 11 report provides seasonal and geographic distributions of wind and wave parameters as well as specific mathematical models by which wave spectra can be developed. The Mediterranean Sea is in ANEP 11 represented by three large regions: western, central and eastern Mediterranean basin. The Adriatic Sea belongs to the central Mediterranean region. However, it should be noted that the central region encompasses much larger area than the Adriatic Sea itself. Consequently, it is expected that wave statistics in ANEP 11 is much more severe comparing to the actual conditions in the Adriatic Sea.

The comparison of the frequencies of occurrence of significant wave heights collected by Cavaleri et al. (1997), ANEP 11 (NATO, 1983) and the results of the present study is shown in Fig. 10. Although the results were obtained in completely different ways, relatively good agreement of histograms collected by Cavaleri et al. (1997) and present data may be noticed. Agreement of results is especially good for higher significant wave heights. For two lowest intervals of significant wave heights (0–0.5 and 0.5–1 m) some discrepancies may be noticed, although the overall frequencies in these two intervals are similar. Discrepancies may be attributed to uncertainties of visual observations of very low significant wave heights and grouping them into these two intervals. Expectedly, the data from ANEP 11 result in considerably higher probability of occurrence of large sea states compared to two other data sources.

Even better comparison can be done if the 3-P Weibull distributions are fitted to the data collected by Cavaleri et al. (1997) and ANEP 11 (NATO, 1983) and then compared to the Weibull distribution from the present study. The resulting Weibull parameters are presented in Table 7, while the corresponding

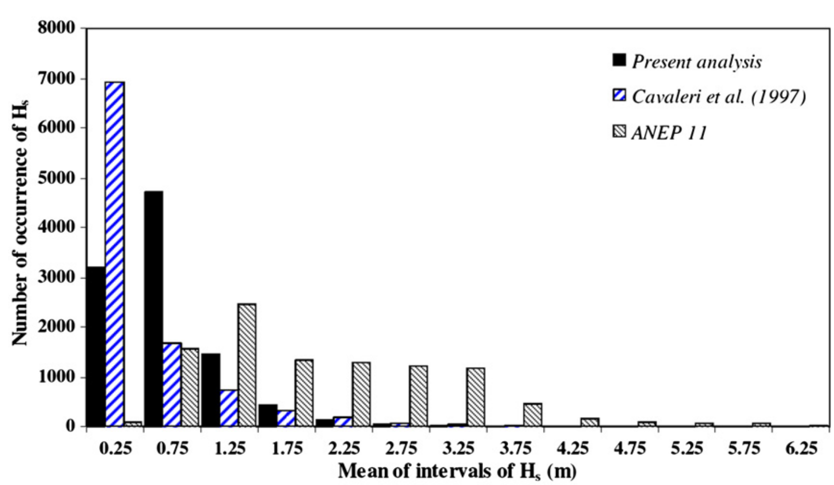

Fig. 10. Comparison of frequencies of occurrence of significant wave heights in the Adriatic Sea.

Table 7
Comparison of parameters of 3-P Weibull distributions.

	ε	α	θ
Present analysis	0.3325	1.015	0.4289
Cavaleri et al. (1997)	0.3952	0.882	0.4258
ANEP 11	0.9159	1.266	0.6986

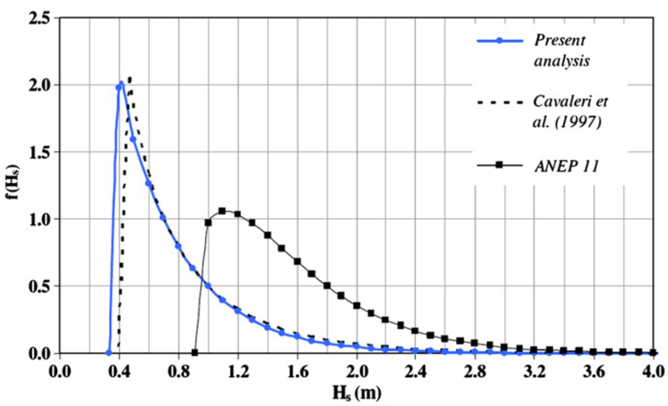

Fig. 11. Comparison of probability density functions.

probability density functions are compared in Fig. 11. Excellent agreement may be noticed in Fig. 11 between distributions based on data of Cavaleri et al. (1997) and the present analysis.

In both analyses valid for the Adriatic Sea significant wave heights above 4 m are rather rare. Thus, in the present analysis 1 out of 10,000 sea states is higher than 4 m. Cavaleri et al. (1997) estimated 5 out of 10,000 sea states higher than 4 m, and they have not reported any sea state higher than 5 m. It should be noted that the location of the wave recording system by Cavaleri et al. (1997) in the Northern Adriatic has the longest fetch for the wind sirocco in the whole Adriatic Sea (750 km), and almost the longest fetch for the bora (100 km). Therefore, the location of measurements is one of the most severe in the Adriatic Sea.

Comparison may be done also with altimeter significant wave height measurement data from six satellite missions covering 14 years, analyzed over the Mediterranean Sea by Queffeulou and Bentamy (2007). The particular sub-basins corresponding to specific geographical topography and local meteorological characteristics are analyzed, including also the Adriatic Sea. For the Adriatic Sea, Queffeulou and Bentamy (2007) provided frequency distribution of significant wave height based on data set of 154,424 measurements collected in satellite missions during the 1992–2005 period. They reported mean significant wave height in the Adriatic Sea of 0.85 m, while 80% of the measured data were less than 1.1 m.

Leder et al. (1998) calculated extreme significant wave heights for different return periods using data of wave height measured in the open part of the Northern Adriatic. The method used by the authors was the approximation of the distribution of monthly extremes by the Gumbel distribution. Monthly extremes were available for the period of 10 years (1978–1986 and 1992). The absolute maximum significant wave height measured in 10 years was 6.58 m recorded during a storm in December 1979. The wave height of 10.2 m was measured during that storm, being the second highest measured wave in the Adriatic Sea. The largest individual wave height recorded so far in the Adriatic Sea reads 10.8 m. The wave was measured in the Northern Adriatic in February 1986 during a storm with a significant wave height of 6.16 m. The theoretical prediction of the most probable extreme significant wave height in 20 and 100 years by Leder et al. (1998) reads 7.20 and 8.57 m, respectively.

It should be mentioned that the data collected by observations from merchant ships, which are analyzed in the present paper, are better suited to the analysis of seagoing ships comparing to the data from the fixed measurement stations (Guedes Soares, 1986, 1996). Guedes Soares (1986) pointed out three important properties of wave data from voluntary observation ships. Firstly, it incorporates the effects of the heavy weather avoidance. Although the severity of sea states in the Adriatic Sea is much lower comparing to the open ocean, sea states with significant wave heights above 5 m are considered to be heavy seas in any case, and prudent ship masters would prefer to avoid them. The effect of the heavy weather avoidance is probably the main reason why the statistics analyzed in the present paper predicts lower extreme values comparing to Leder et al. (1998). The second advantage of data from transiting ships is that such data are collected along the trade routes used by merchant ships, where the need for information is greatest. Finally, the third advantage is that the estimates of mean values are likely to have no bias, as elaborated by Guedes Soares (1986).

One notice should be made also on the accuracy of the visual observations of significant wave heights. Guedes Soares recommended following regression expression to calibrate visually observed significant wave height to measurements (Guedes Soares, 1986)

$$H_S = 2.33 + 0.75 H_V \tag{18}$$

where H_S is the measured significant wave height, while H_V is the visually observed significant wave height. Thus, for the visually observed wave height of 4 m, the measured significant wave height would read 5.33 m. Therefore, from this aspect the analysis presented in the paper is un-conservative. However, Eq. (18) is obtained for ocean seas and basically intended to predict uncertainty in observations of much higher significant wave heights. It is questionable whether it is applicable directly for sea states in coastal waters. Nevertheless, this consideration is to be mentioned for the completeness of all relevant aspects.

It should be emphasized that the present study is applicable in the first place for seakeeping studies of ships. For the analysis of offshore structures in the Adriatic Sea, statistics developed in the paper should not be used, as there could be a significant variability between different locations in the Adriatic Sea. A typical example is comparison of studies by Cavaleri et al. (1997) and Leder et al. (1998) where the latter study reports much larger extreme significant wave heights, although both of them refer to the Northern Adriatic. In case of the offshore structure analysis, wave statistics should be obtained by long-term wave measurement on a specific location where the structure is to be installed. However, in the case of lacking such data, the present results may be useful.

9. Conclusion

The paper presents the probabilistic description of sea state occurrences in the Adriatic Sea. A probabilistic model is developed based on observations from merchant ships during 15 years. Although the data were collected a relatively long time ago, they have not been incorporated in a histogram of sea states until know. Nowadays, there is a great need for them by the industry due to the safety and commercial reasons. The probabilistic description of the wave environment is a prerequisite for successful implementation of structural reliability methods for damaged ships. Also, recently introduced EU maritime regulations require the histogram of sea states for decisions about retrofitting of existing RO-RO ships. Finally, the industry of small and pleasure boats has been rapidly developing in the countries having access to the Adriatic Sea. Developed statistics of sea states could contribute to the improvement of their safety and of the seakeeping performances.

The results of the analysis show that sea states with significant wave heights between 0.5 and 1 m are the most frequent in the Adriatic Sea. Sea states with significant wave heights larger than 4 m were observed quite rarely, while significant wave heights larger than 5 m were almost never encountered by the merchant ships. More severe sea states, up to significant wave heights of 7 m, were recorded only by the measurements from fixed offshore platforms. This indicates that the results presented in the paper are applicable for seagoing ships, while their usage for the analysis of offshore structures is limited and should be done with great care. In addition, one should bear in mind that visually observed significant wave height may differ considerably from measured values due to the uncertainty in visual wave observations.

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