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Ecological study of gas fields in the northern Adriatic

3. Surface waves

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The paper deals with the surface wave data recorded in the area of gas fields IVANA and IKA from 1978 to 1984 and partly from 1985 to 1986. It includes calculations of relative and cumulative frequencies of wave heights and periods and height distribution per seasons. Statistical analysis of the wave height, periods and length was made for extreme speeds of characteristic winds, the Bora and Scirocco. The wave spectra were calculated from digitized records, with parameter approximation. Finally estimates of extreme values of significant wave heights are given.

3.1. INTRODUCTION

Characteristics of surface waves are described from two aspects. The first refers to average characteristics of surface waves per seasons and annually. The second part deals with the characteristics of surface waves during extreme situations recorded so far. The data obtained from the measurements in conditions with maximum wind are compared to the data obtained from the forecast of return periods for extreme values of wave heights.

For these investigations the surface wave data recorded from 1978 to 1984 onboard the platform PANON in the northern Adriatic were used. In addition to the above mentioned database, the data recorded from 1985-1986 were used, primarily for extreme cases.

In the description of surface waves in working conditions, the results of climatological-statistical analysis of the surface wave heights and periods were used, regardless of the wind speed and direction. Climatological data were used to calculate probability functions for waves of certain direction.

For extreme conditions, distribution functions of wave height and period were analyzed separately for the Bora and Scirocco, which are the two major winds in the researched area, as far as wind generation is concerned. For the analysis of extreme sea states, synoptic situations with NE and SE winds (Bora or Scirocco), blowing more than 12 hours at a speed over 15 m s^{-1}, at least during one synoptic term, were used.

Of particular importance for marine structures is a knowledge not only of a total energy of surface waves, but also of wave energy distribution dependent upon period or frequency (spectra). This paper will therefore give approximation of the surface wave spectrum by a selected function of the wind speed and frequency, which enables a simple calculation of the surface wave spectrum if the wind speed is known. The function has been tested on measured spectra for all the wind speeds.

3.2. MATERIAL AND METHODS

Wind generated sea level oscillations were recorded by DATAWELL WAVERIDER - Netherlands. The data were recorded in an analogous form on the paper tape, in synoptic terms (01, 04, 07 etc.). Length of records in synoptic terms was 5, 10 minutes or more, depending on the wind speed or the wave height. When the wave height was below 1 meter the record length was 5 minutes, while for the wave heights over 1 meter the length record was 10 minutes or more.

About 10000 records of sea level oscillations (length 5, 10 minutes or more), and wind vectors measured between January 1978 and December 1984 were used for the surface wave analysis. In this period the waverider was working with interruptions, which were mainly due to objective reasons (repair or transfer of the platform, instrument failure, etc.). Measurement intervals of the wind generated sea level oscillations in that period are shown in Fig. 3.1.

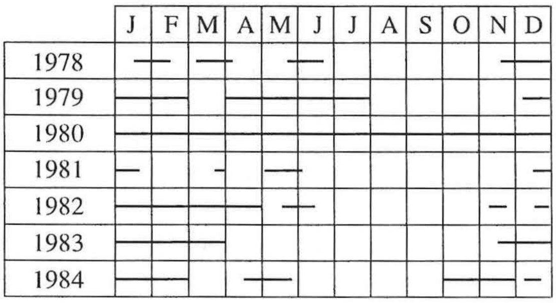


Fig. 3.1. Wave recording intervals

Analogous sea level records for the analysis of wind waves were digitized in the time intervals of 1 second, while the method of wind analysis is given in the preceding chapter.

Measurements were performed in the area of the gas fields, mainly in the field IKA, in location:

$$\varphi = 44°20'06''\,N$$
$$\lambda = 13°34'07''\,E$$
$$d \approx 50\,m$$

Short definitions of the parameters to be used in analyses and descriptions of the sea states are given for an easier understanding of the text.

Symbol	Term and definition
ω	Angular frequency (work s^{-1})
f	Frequency (Hz), reverse period value.
Hs or $H_{1/3}$	Significant height, arithmetic mean value of 1/3 of the highest heights in a record. It can be obtained directly from records, that is by spectral analysis, using the relation:
$H_{1/10}$	Arithmetic mean value of 1/10 of the highest heights in a record.
H_{max}	Maximum height in a record.
T_{sr}	Mean or significant wave period, arithmetic mean value of all the periods in a record, which is obtained directly from readings or by spectral analysis, using the relation:
L_{sr}	Mean wave length, a mean value of all the lengths in a record, the lengths being calculated using the relation:

$$H_{1/3} = 2.83\sqrt{2m_0} \qquad m_0 = \frac{1}{2}\int_0^{\infty} s(\omega)\,d\omega$$

$$T_{sr} = 2\pi\frac{m_o}{m_1} \qquad m_1 = \frac{1}{2}\int_0^{\infty} S(\omega)\,\omega\,d\omega$$

$$L_{sr} = g\frac{T_{sr}^2}{2\pi}$$

T_C Period between the two zero line intersections in a record, which is obtained directly from readings or by spectral analysis, using the relation:

$$T_c = 2\pi\sqrt{\frac{m_o}{m_2}}$$

T_Z Period obtained by spectral analysis using the relation:

$$T_z = 2\pi\sqrt{\frac{m_2}{m_4}}$$

T_{max} Maximum period in the surface wa ve spectrum

P_f Factor of the spectrum conception, obtained by the relation:

$$P_f = \frac{2}{m_0}\int_0^{\infty} f\left[S(f)\right]^2 df$$

3.3. RELATIVE AND CUMULATIVE FREQUENCIES OF WAVE HEIGHTS AND PERIODS

All the synoptic situations with a wind of constant direction blowing more than 12 hours were used for calculations of significant heights and mean periods, applying the data of direct measurements. From the whole statistical model of heights and periods distribution functions were calculated, particularly for the situations with the Bora (ENE, NE, and N wind) and Scirocco (SE and ESE wind), because of a dominant frequency and speed of these winds.

In Fig. 3.2. sectors of direction of blowing for dominant winds are given, showing that in the researched area the fetch is several times longer for the Scirocco than for the Bora.

Fig. 3.2. Fetch for SE wind (Scirocco), and NE wind (Bora)

Function of relative and cumulative frequency was calculated for heights. Cumulative frequency was obtained by adding up relative frequencies from higher heights to the lower ones, which offers a possibility of determining probability of the heights higher than some selected values.

The results of these calculations are shown in Figures 3.3. and 3.4.

Comparison of relative and cumulative frequencies of the wave heights between the Bora and Scirocco shows that with the Scirocco considerably higher heights are possible than with the Bora. If for instance, a height of 3 meters is taken as a limit, it is evi-

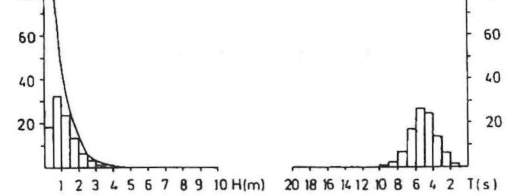


Fig. 3.3. Relative and cumulative frequencies of wave periods (T), and heights (H) for the interval January 1978 through March 1984 - NE wind

dent that with the Bora probability of heights higher than the limit is 3%, while with the Scirocco such probability is even about 13%.

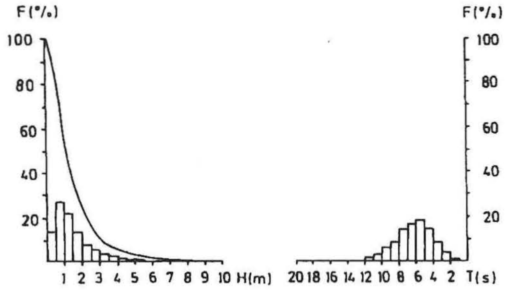


Fig. 3.4. Relative and cumulative frequencies of wave periods (T), and heights (H) for the interval January 1978 through March 1984 - SE wind

As a result, relative frequency function shows higher values in the maximum for the Bora than for the Scirocco, so that probability of wave heights in the class 0.5 - 1 meter is above 33% for the Bora, and about 27% for the Scirocco.

In the situations with Scirocco maximum heights occur in the class 9.5 - 10.0 m, while in the situations with Bora they occur in the class 7.0 - 7.5 m. In the situations with Scirocco higher periods than in the situations with Bora are possible according to relative frequency function. With the Scirocco the most frequent periods occur in the class 5.0 - 7.0 seconds, while with the Bora function of the period relative frequency has its maximum in an interval between 4.0 and 6.0 seconds.

The width of relative frequency is greater for the Scirocco than for the Bora, which is the consequence of a higher probability of higher periods in the situations with the Scirocco.

3.4. FUNCTION OF HEIGHT DISTRIBUTION PER SEASONS

In this analysis the data of extreme values of wave heights per hours were used, from all the available records from 1978 to 1984.

In such a way a random sample of extreme values per measurement terms was obtained for the entire recorded material. This random sample served for calculation of surface wave heights.

In Figures 3.5. and 3.6. mean seasonal functions of relative height frequency are given. The graphs clearly indicate seasonal variations in the function form. By characteristics of distribution function, annual interval can be divided into 4 seasons (WINTER: January, February and March; SPRING: April, May and June; SUMMER: July, August and September; AUTUMN: October, November and December).

Fig. 3.7. gives a graphic representation of a mean annual value of this function. A common characteristic of all the described functions is the highest frequency of the wave heights up to 1 meter. However, probability

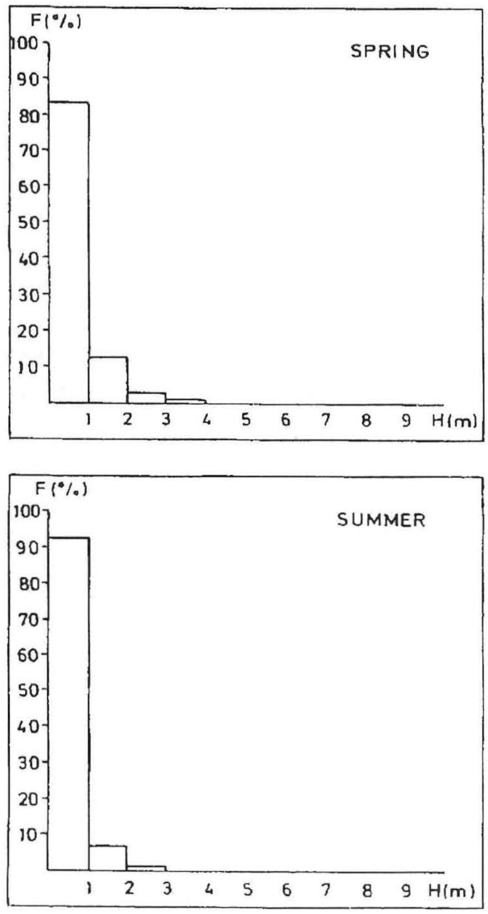
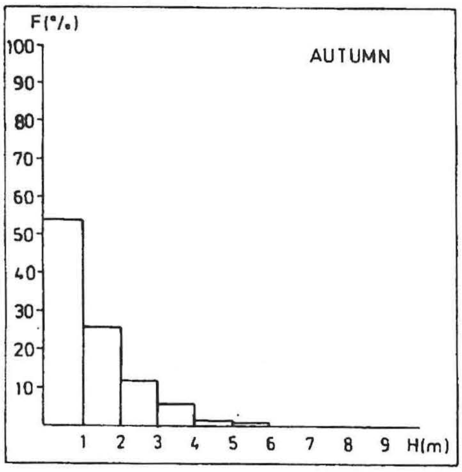


Fig. 3.5. Relative frequencies of wave heights (H) for different season



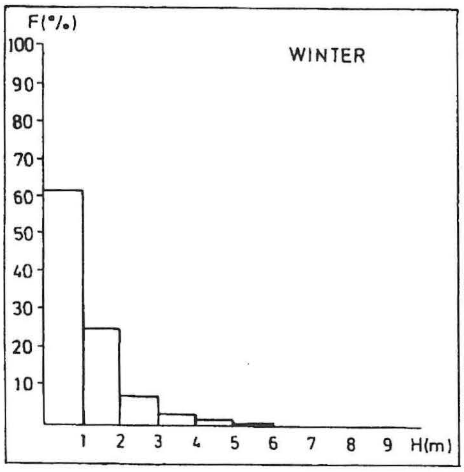


Fig. 3.6. Relative frequencies of wave heights (H) for different season

of heights up to 1 meter varies from one season to another, so that the highest probability is in summer (over 90%), while the lowest one is in autumn (about 55%). This is the result of seasonal variations in the wind field. Summer season is characterized by a great number of calm days, that is with a weak wind, while the strongest winds and the smallest number of calm days occur in autumn and winter.

Comparison of the function of height frequency in winter and autumn shows that in winter there is a higher probability of the wave height up to 1 meter than in autumn. However, in winter occur higher waves than in autumn. Therefore it can be concluded that the number of days without wind or with a weak wind is higher in winter than in autumn, and at the same time in winter situations with a stronger wind occur.

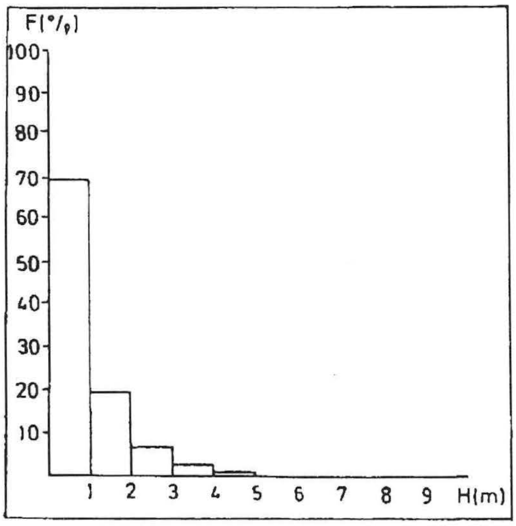


Fig. 3.7. Annual relative frequencies of wave heights (H)

3.5. STATISTICAL ANALYSIS OF THE EXTREME BORA AND SCIROCCO SURFACE WAVES

From a random sample of the situations with Bora and Scirocco over a seven-year period, two situations in which the extreme wave height values were recorded have been extracted.

Tables 3.1 and 3.2. show numerical values of all parameters obtained by direct reading of the records from the beginning until the end of these situations.

It is evident that the highest recorded wave height over a seven-year period is 7.2 meters for the Bora, and 10.2 meters for the Scirocco, which is the highest recorded wave height in the Adriatic. In these terms all the other parameters describing the sea state also assume extreme values, e.g. a wave 10.2 m high is about 130 m in length.

Table 3.1. Statistical analysis of surface waves for Bora wind (NE)

STATION : PANON
DATE : 07.01.1981. - 09.01.1981.
WIND : NE, 7.0 - 17.4 m/s

HOUR	$H_{1/3}$ (m)	$H_{1/10}$ (m)	H_{MAX} (m)	H_M (m)	T_M (s)	L_M (m)
1300	1.01	1.32	1.80	0.63	4.76	35.31
1600	1.97	2.52	3.30	1.31	5.21	42.39
1900	2.13	2.54	2.70	1.41	5.65	49.91
2200	2.19	2.86	3.40	1.45	5.46	46.50
0100	2.17	2.66	2.80	1.44	5.69	50.49
0400	2.32	2.94	3.40	1.53	5.47	46.78
0700	2.52	3.10	3.50	1.61	6.00	56.21
1000	3.61	4.50	4.90	2.23	6.08	57.62
1300	3.87	4.55	5.00	2.61	6.28	61.54
1500	3.38	4.01	5.30	2.29	6.02	56.55
1600	3.67	4.98	5.70	2.35	6.52	66.38
1900	3.87	4.81	7.20	2.51	6.43	64.52
2200	3.55	4.36	5.50	2.39	6.47	65.38
0100	3.41	4.02	4.60	2.31	6.50	65.97
0400	2.86	3.62	4.60	1.97	5.97	55.62
0700	2.90	3.91	5.10	2.00	7.21	81.19
1000	1.42	1.70	1.90	0.93	5.43	46.03
1300	1.65	2.02	2.10	1.14	5.13	41.08
1600	1.42	1.88	2.20	0.88	5.11	40.75
1900	1.03	1.37	1.80	0.63	4.61	33.15
$H_{1/3}$, $H_{1/10}$, H_{MAX}, H_M, T_M, L_M FOR WHOLE SITUATION	2.85	3.84	7.20	1.63	5.73	51.28

Table 3.2. Statistical analysis of surface waves for Scirocco wind (SE)

STATION : PANON
DATE : 21.12.1979. - 23.12.1979.
WIND : ESE-SE, 3.3 - 19.1 m/s

HOUR	$H_{1/3}$ (m)	$H_{1/10}$ (m)	H_{MAX} (m)	H_M (m)	T_M (s)	L_M (m)
1900	0.79	0.98	1.20	0.52	5.87	53.83
2200	2.32	2.88	3.30	1.64	6.89	74.08
0100	4.08	5.40	6.10	2.74	7.62	90.73
0400	4.64	6.03	7.10	2.90	8.26	106.45
0700	6.47	7.95	8.70	4.23	9.40	137.86
0800	5.46	7.52	8.80	3.45	8.81	118.38
0900	7.34	8.97	10.20	4.88	8.87	122.87
1000	5.35	6.93	9.60	3.66	9.17	131.33
1100	5.21	6.45	7.20	3.16	9.40	137.81
1300	5.52	7.40	7.90	3.73	9.90	153.02
1600	4.64	5.40	5.90	3.05	10.00	156.13
1900	3.24	3.63	3.70	2.21	7.99	99.65
2200	3.92	5.37	5.40	2.49	8.05	101.11
0100	2.65	3.23	3.30	1.69	7.30	83.09
0400	2.03	2.43	2.70	1.48	6.64	68.79
0700	1.54	2.08	2.40	1.01	5.88	53.94
1000	1.57	1.95	2.10	0.97	6.24	60.80
1300	1.37	1.70	2.00	0.83	6.36	63.13
1600	0.90	1.03	1.10	0.62	7.12	79.14

$H_{1/3}$, $H_{1/10}$, H_{MAX}, H_M, T_M, L_M FOR WHOLE SITUATION					
4.72	6.54	10.20	2.53	8.00	100.01

3.6. CHARACTERISTICS OF FORM AND EVOLUTION OF THE SURFACE WAVE SPECTRUM

Spectra of sea level heights give distribution of potential energy, depending on frquency. From digitized records surface wave spectra for all measurement terms were calculated, using the Blackman and Tukey's method (1958). The method of digitizing and spectral analysis used in the data analysis was described in detail by SMIRČIĆ (1978, 1981) SMIRČIĆ and GAČIĆ (1982).

Spectral analysis was made on all the digitized records (about 400 spectra).General characteristic of the measured spectra is an increase in the wave energy, or the maximum, with an increase in the wind speed. At the same time, the position of maximum is shifted toward lower frequencies and higher periods. A typical characteristic of the analyzed spectra is an absolute energy maximum, which is mainly the result of a direct wind action. As a result of swell impact, secondary maximum occurs, but in rare situations.

This means that the energy of the sea level oscillations results mainly from the local wind. In order to illustrate the evolution of spectrum and form, in Figures 3.8. to 3.11. spectra are shown for a situation with Scirocco and a situation with Bora. Each situation is given in two parts: from the beginning to the maximum of the wind speed or the wave energy, and from the maximum to the absence of wind.

In the period of development of the wave system the Bora and Scirocco waves show the same characteristic, i.e. the above mentioned shifting of the spectrum maximum toward lower frequencies. The period of decrease in the energy of wind, and consequently the waves, is characterized by shifting of the spectrum maximum toward higher frequencies during the Bora, while with the Scirocco, in this interval, the maximum practically remains on the same frequency. Furthermore, comparing the spectra of Bora and Scirocco, it is evident

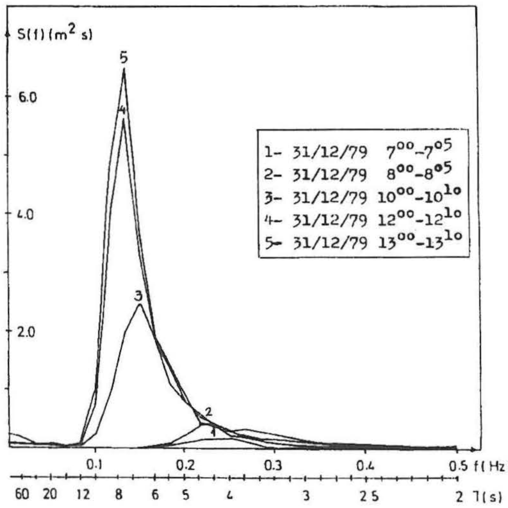


Fig. 3.8. Evolution of wave spectra for a situation with Bora (interval of wind speed and wave energy increase)

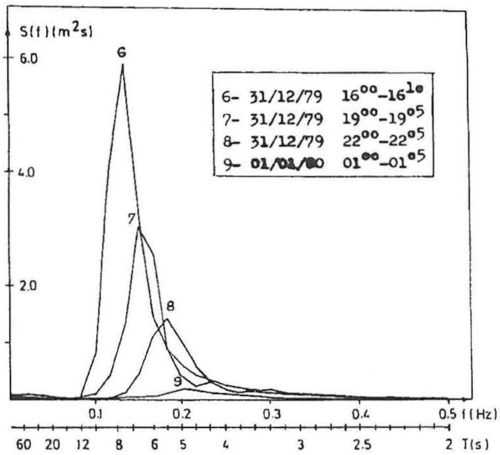


Fig. 3.9. Evolution of wave spectra for a situation with Bora (interval of wind speed and wave energy decrease

that the maximum in the Bora spectra occur in shorter periods than the maximum in the Scirocco spectra. In the Scirocco wave spectra a typical period of the energy maximum is in the interval between 7.0 and 10.0 seconds, while the period of the maximum energy in the Bora wave spectrum is in the interval between 6.0 and 8.0 seconds.

The described characteristics of evolution of the surface wave spectrum can be observed in the situations with smooth increase and decrease of the wind speed. However, if the wind increase or decrease is not smooth (situations with several day's wind duration) or if the wind direction is changed rapidly, the surface wave spectra show secondary maximum, while the maximum frequency do not follow smoothly the wind.

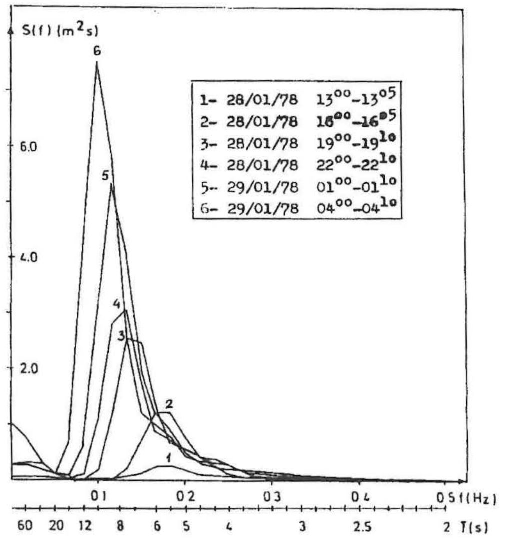


Fig. 3.10. Evolution of wave spectra for a situation with Scirocco (interval of wind speed and wave energy increase)

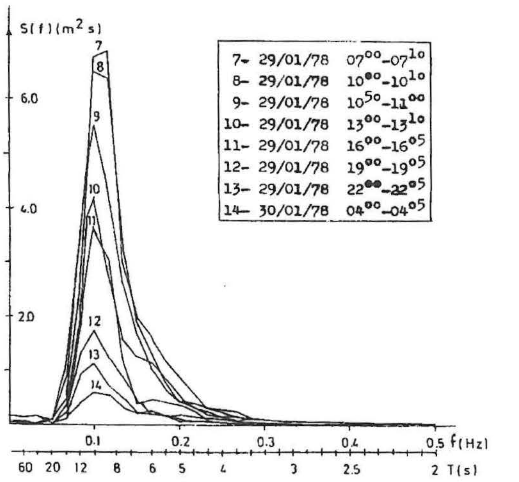


Fig. 3.11. Evolution of wave spectra for a situation with Scirocco (interval of wind speed and wave energy decrease)

With an increase of energy or surface wave significant height, the value of wave spectrum maximum period is increased as well (Tmax).

Investigations have shown that there are different relations that connect the values of maximum period of wave spectrum and significant height, depending on fetch or wind duration.

In order to obtain a functional relation between the maximum period and significant height for the northern Adriatic, a least square method was used to design the function representing such relation. Using all the available pairs of these values (about 250 pairs), in Fig. 3.12. diagram of relation between the significant height and the period of maximum is shown, as well as the curve obtained by a least square method. It is evident from the Fig. 3.12. that the relation between these values is relatively well described by the curve, and that deviations are somewhat increased for high values of significant heights and spectrum maximum period.

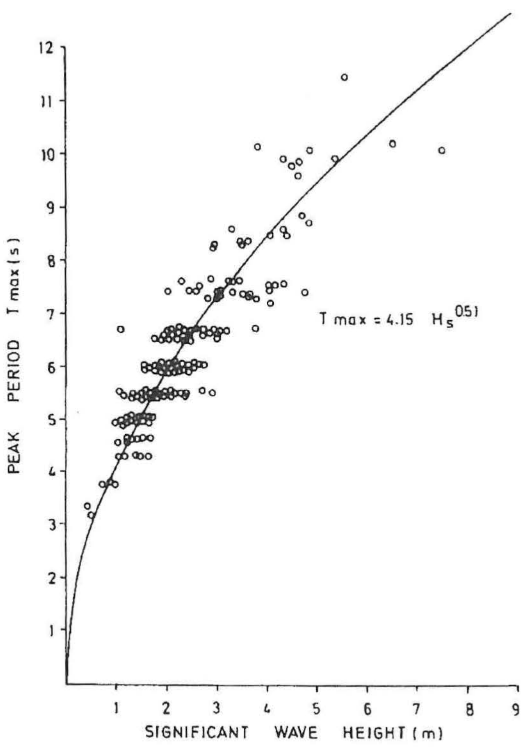


Fig. 3.12. Significant wave height as a function of the peak period

3.7. PARAMETER APPROXIMATION OF THE SURFACE WAVE SPECTRUM

The measured spectra can be synthesized so that they are approximated by an analytical function which depends upon few physical parameters. In that respect a series of one-dimensional surface wave spectra has been developed so far, such as the spectrum of DARBYSHIRE (1952), NEUMANN (1952), PIERSON AND MOSKOWITZ (1964), HASSELMANN, *et al.* (1973).

As it has been pointed out, this part of investigation deals with one-dimensional spectrum, that is the spectrum in which the surface wave energy is a function of one variable, i.e. frequency.

All the above mentioned approximations are based on a dimensional analysis of the wave spectrum developed by PHILIPS (1977), assuming that in a part of the spectrum in the area of frequencies higher than the maximum frequency, there is a balance of the received energy and the energy that is lost and redistributed by various dissipation processes. This part of the spectrum depends only on frequency and acceleration of gravity, because it is an area of gravity waves. It is also called saturated part of the spectrum because of a balance of the received and lost energy.

According to dimensional analysis, the wave energy in the area of gravity waves is decreased with the fifth power of frequency:

$$S(f) = \alpha g^2 f^{-5}$$

Deviation from this relation occurs only in case of the seabed or current impact, as shown by KITAIGORODSKII (1975).

In some last ten years, experimental confirmations of these assumptions have shown that the wave energy in a high-frequency part of the spectrum also depends on the wind speed. In this case, based on dimensional analysis, the wave energy must decrease with the fourth power of frequency, as defined by KAHMA (1981):

$$S(f) = \alpha_u g U_{10} f^{-4}$$

where for α, he got 4.5 x 10^{-3}.

With this relation most of the authors use the wind speed values reduced to a height of 10 meters above sea level, because it is presumed that at this height the wind does not depend on the transport of the momentum of motion from the air into the sea.

Past investigations in the Adriatic (SMIRČIĆ *et al.*, 1983) have shown that slope of high-frequency part of the spectrum is really very close to the value -4. It should be pointed out that only the spectra obtained from the records of 10 minutes and more were used, for the situations without swell, or the situations in which dimensionless frequency was higher than 0.13. Dimensionless frequency was defined by:

$$\nu = \frac{f_m U_{10}}{g}$$

Jonswap's parameter spectrum (HASSELMANN *et al.*, 1973), which proved to be a good approximation of measured spectra in different fetch and wind duration conditions, will be tested here.

Considering that slope of a high-frequency part of the spectrum in the northern Adriatic is -4 has been established on an experimental basis, one modification of JONSWAP spectrum with respect to this fact will be tested. The relation for JONSWAP spectrum is:

$$S(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left\{-\frac{5}{4}\left(\frac{f_m}{f}\right)^4 + \gamma \exp\left[\frac{-(f-f_m)^2}{2\sigma^2 f_m^{\,2}}\right]\right\}$$

where:

α - PHILLIPS dimensionless constant,
g - gravity acceleration,
f_m - frequency of the spectrum maximum,
γ - intensification factor of the maximum
σ - spectrum width coefficient

The modification, considering the fact that slope of the spectrum high-frequency part is -4, has the following form:

$$S(f)=\alpha g U_{10}(2\pi)^{-4}f^{-4}\exp\left\{-\frac{5}{4}\left(\frac{f_m}{f}\right)^4+\gamma\exp\left[-\frac{(f-f_m)^2}{2\sigma^2 f_m^2}\right]\right\}$$

Each symbol has the same meaning as in the previous relation, while the dependence of the spectrum high-frequency part on the wind speed (U_{10}) has been introduced. Thus, parameter presentation of the measured spectra has been reduced to determining the values of three free parameters:

- Phillips' dimensionless constant α, enhancement factor of the maximum γ and spectrum width coefficient σ.

The value given by HASSELMANN et al., 1973 was taken for the spectrum width coefficient, with JONSWAP spectrum, while the other two parameters were determined from the measured spectra for the northern Adriatic. Enhancement factor of the maximum was determined for each term, as a ratio of the real spectrum to the PIERSON-MOSKOVITZ spectrum in a 0.9 f_m to 1.1 f_m frequency interval. Coefficient was determined using the relation:

$$\alpha = S_m(f)/g^2(2\pi)^{-4}f^5\exp\left\{-\frac{5}{4}\left(\frac{f_m}{f}\right)^4+\gamma\exp\left[-\frac{(f-f_m)^2}{2\sigma^2 f_m^2}\right]\right\}$$

where S_m (f) is the value of measured spectrum.

Coefficient α was determined as a mean value in a 1.35 to 2.0 f_m frequency interval. The value of this coefficient for the Bora, or Scirocco in the northern Adriatic was obtained as an arithmetic mean value of this constant in all cases. Intensification factor of the maximum was calculated in the same way. Values of the coefficients α and γ for JONSWAP spectrum are shown in Table 3.3.

Coefficient α for the modified form spectrum was also calculated in a 1.35 f_m to 2 f_m frequency interval, as an arithmetic mean value using the relation:

$$\alpha=S_m(f)/gU_{10}(2\pi)^{-4}f^{-4}\exp\left\{-\frac{5}{4}\left(\frac{f_m}{f}\right)^4+\gamma\exp\left[-\frac{(f-f_m)^2}{2\sigma^2 f_m^2}\right]\right\}$$

Enhancement factor of the maximum was calculated as a ratio between the real spectrum and the spectrum of the following form:

$$S(f)=\alpha g U_{10}(2\pi)^{-4}f^{-4}\exp\left\{-\frac{5}{4}\left(\frac{f_m}{f}\right)^4\right\}$$

again in a 0.9 f_m to 1.1 f_m frequency interval, as with JONSWAP spectrum. The obtained coefficients α and γ for the modified spectrum (SG spectrum) are also shown in Tab. 3.3.

When calculating SG spectrum, the value 0.2 was taken as a coefficient of the spectrum width (σ).

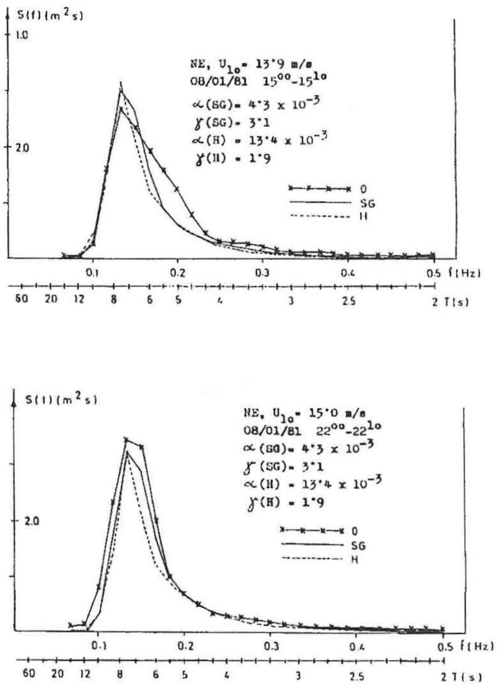


Fig. 3.13. Observed, JONSWAP (H) and modified (SG) spectrum for different wind conditions (parameters to spectral estimates, dates and wind speed and directions are denoted at upper right corner of the graph)

Table 3.3. Values of coefficients α and γ for JONSWAP spectrum and SG spectrum

	JONSWAP		SG	
	Bora	Scirocco	Bora	Scirocco
α	4.3×10^{-3}	3.2×10^{-3}	13.4×10^{-3}	11.1×10^{-3}
γ	1.9	1.8	3.1	2.9

The values of real spectrum and both parameter approximations were compared, using the relations (1) and (2) and the parameter values shown in Table 3.3. The results of such comparisons are shown in Figures 3.13. - 3.15.

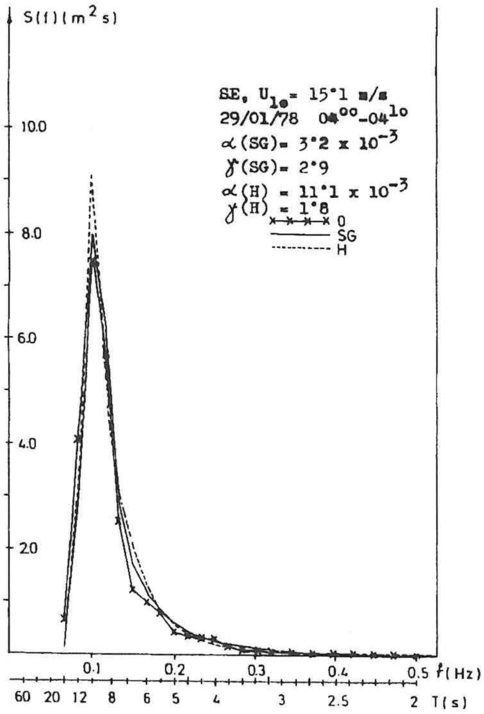


Fig. 3.14. Observed, JONSWAP (H) and modified (SG) spectrum for different wind conditions (parameters to spectral estimates, dates and wind speed and directions are denoted at upper right corner of the graph)

From extensive material four hours were selected (2 for the Bora and 2 for the Scirocco). These examples show that both parameter presentations relatively well approximate the real spectra.

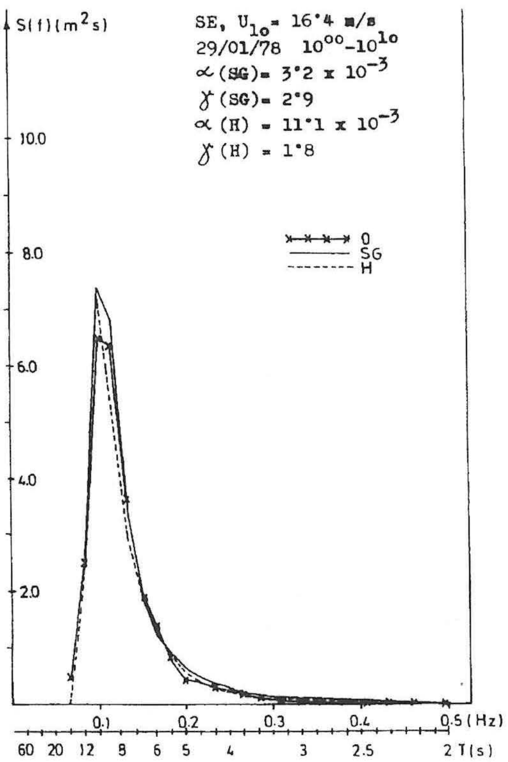


Fig. 3.15. Observed, JONSWAP (H) and modified (SG) spectrum for different wind conditions (parameters to spectral estimates, dates and wind speed and directions are denoted at upper right corner of the graph)

Having examined all the analyzed material (about 250 spectra), it was noted that the width of JONSWAP spectrum was insufficient as compared with the measured spectra in the northern Adriatic. On the other hand, SG spectrum relatively well approximates the real spectra of the northern Adriatic in width, but it underestimates the energy of maximum with relatively low wind speeds.

In order to compare efficiency of approximation of the real spectrum by either of the two parameter, the following coefficient was calculated:

$$R = \sqrt{\sum_{i=1}^{N}\left[S(fi) - S_m(fi)\right]^2} \,/\, \sum_{i=1}^{N} S(fi)$$

giving a ratio of the difference between the real spectrum and parameter presentation, to the value of the spectrum parameter presentation. The greater the coefficient, the worse is approximation of the real spectrum by parameter spectrum.

Ratio of coefficients R for JONSWAP spectrum (R_H) and SG spectrum (R_{SG}) makes it possible to compare efficiency of approximation of the real spectrum by either of the two parameter approximations.

Fig. 3.16. gives a graphic representation of the ratio of coefficients R_{SG} and R_H as a function of significant height, so as to show efficiency of approximation by either of the two parameter presentations, depending on the wave energy. If the ratio is higher than one, JONSWAP spectrum is better than SG spectrum in approximating the real spectrum. If the ratio is lower than one, SG spectrum is better than Jonswap's spectrum in approximating the real spectrum.

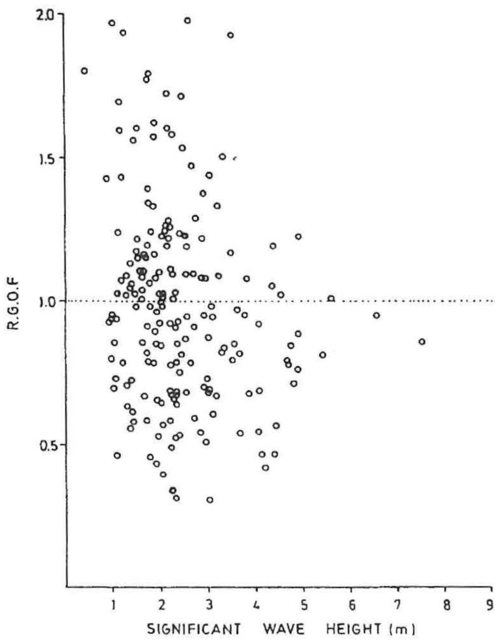


Fig. 3.16. The ratio of goodness of fit (R.G.O.F.) of the JONSWAP spectrum to that of the modified spectrum as a function of significant wave height

It is evident that there is not a regularity in the relation between the ratio and significant height. However, it can be noted that the ratio is in most cases lower than one, which means that in general SG spectrum approximates the real spectra more efficiently.

3.8. ESTIMATE OF EXTREME VALUES OF SURFACE WAVE SIGNIFICANT HEIGHTS

Calculations of extreme return values of wave heights for the northern Adriatic were made on the basis of the data collected from 1978 to 1984, using the method explained in the work by CARTER and CHALLENOR, 1980. Input data for calculation of return values were monthly extreme values of significant wave heights obtained from analogous records. The method by which significant wave heights have been obtained includes reading of the highest wave crest and the lowest wave trough in a given record, and the number of zero points on the sea surface record curve. Significant height is then derived from the following relation:

$$Hs = a\,(b+d)$$

where "b" is the height of crest above zero line in meters, while "d" is a distance from the deepest trough to zero line. Coefficient "a" is a constant which depends on the number of zero points. This method of estimating the significant height from an analogous record is presented in the paper by DRAPER (1966).

In this way monthly extreme values of significant wave heights were obtained for the months completely covered by measurements. For the months with wind records but without wave records, significant wave height was calculated from the extreme wind speed for that month, using linear relation between the wind speed and the significant wave height obtained in previous investigations (SMIRČIĆ and GAČIĆ, 1982). A total seven-year random sample includes monthly extreme values for 60 months from the 84 total.

Table 3.4 shows monthly extreme values used for calculation of extreme return values of significant wave heights, for each of the seven years.

Return values of significant wave heights for each month were obtained by approxima-

Table 3.4. Monthly significant wave height maximum (m)

YEAR: MONTH:	1978	1979	1980	1981	1982	1983	1984
1	5.12	2.81	3.75	4.46	2.41	5.00	2.77
2	4.28	3.17	1.82		1.71	4.09	1.56
3	1.59	2.30	2.77		3.35	3.84	
4	3.20	2.36	2.44	1.56	3.02		1.95
5	2.28	2.68	2.55	1.32	1.69		2.11
6		1.95	1.59	3.90	1.69		
7		3.90	1.59		2.80		
8		3.00	2.11		3.90		
9		3.20	1.46	4.20	3.00		
10		2.10	3.54	4.70			1.89
11	3.42		3.65	3.90	5.30		3.22
12	3.13	6.58	3.47	3.60	5.20	5.15	

tion of cumulative distribution function by GUMBEL function:

$$P(X < x) = \exp\left\{-\exp-\left[(x-A)/B\right]\right\}$$

where coefficient A and B were obtained by linear regression, while P is cumulative distribution function of variable x.

From the obtained values of A and B coefficients for each month, annual return values of significant wave heights were calculated for the periods of 50 and 100 years respectively, using the relation:

$$P(X < x) = \prod_{m=1}^{M} \exp\left\{-\exp\left[(x-A_m)/B_m\right]\right\}$$

Probability of a certain height for N years is:

$$P = 1 - 1/N$$

In Table 3.5. the 50-year return values of significant heights are shown for each month in a year.

Table 3.5. 50-year return value Hs

Month	No. max.	H_s (m)
I	7	6.93
II	6	6.74
III	5	6.53
IV	6	5.02
V	6	4.49
VI	4	5.07
VII	3	5.57
VIII	4	7.17
IX	4	6.45
X	4	7.07
XI	5	8.55
XII	6	9.25

The 50-year and 100-year return values were calculated only from monthly extreme values for autumn-winter period (from November to April). Such choice was made for two reasons. First, this period is characterized by synoptic situations with stronger winds than in the rest of the year. Secondly, the data for the summer period are much fewer than for the selected period, in other words, in summer season there is a relatively high number of monthly extreme values of significant heights calculated from the wind speed values. Thus, an error entered because of the assumption that there is a linear connection between the wind speed and significant height, has been eliminated. Figures 3.17. to 3.20. show cumulative distribution function of significant wave heights and its approximation by straight line, using a method of deviation square minimum for every month (from November to April). In Table 3.6. extreme return values of significant heights are given for the periods of 5 to 100 years, calculated according to the above mentioned method.

Table 3.6. Extreme return values of significant heights for the periods of 5, 10, 20, 50 and 100 years

Return period (year)	H_s (m)
100	11.49
50	10.37
20	8.88
10	7.78
5	6.60

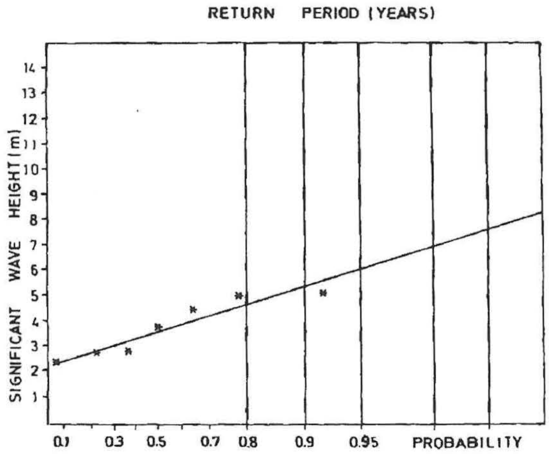


Fig. 3.17. Approximation of cumulative distribution function of extreme values of significant wave heights for January

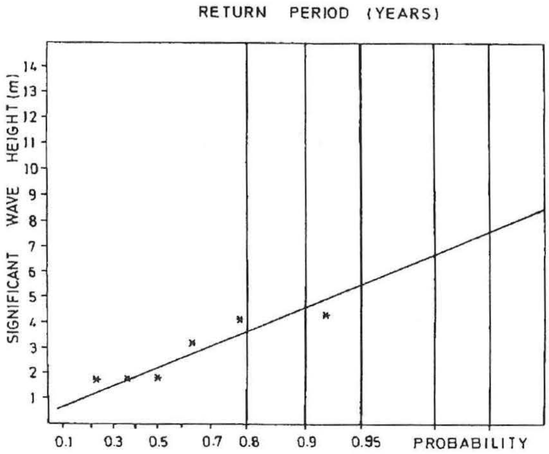


Fig. 3.18. Approximation of cumulative distribution function of extreme values of significant wave heights for February

It should be emphasized that these values are extreme return values of significant heights, which can be multiplied by the factor f= 1.58 to obtain maximum heights. As random sample is relatively small, analyses of extreme values were not made separately for the Bora and Scirocco, although such analyses would give more precise results. It is obvious that the extreme values caused by the Bora and Scirocco represent the elements of two different random samples, therefore they should be analyzed separately.

In spite of all defaults of the input random sample (relatively short measurement series and unhomogeneous random sample) it can be concluded that the obtained extreme return values of significant heights are real and applicable in practice.

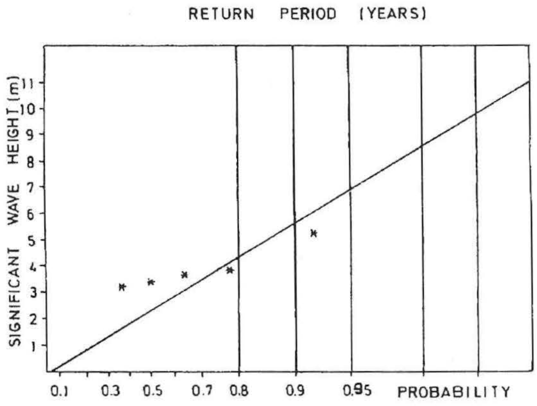


Fig. 3.19. Approximation of cumulative distribution function of extreme values of significant wave heights for November

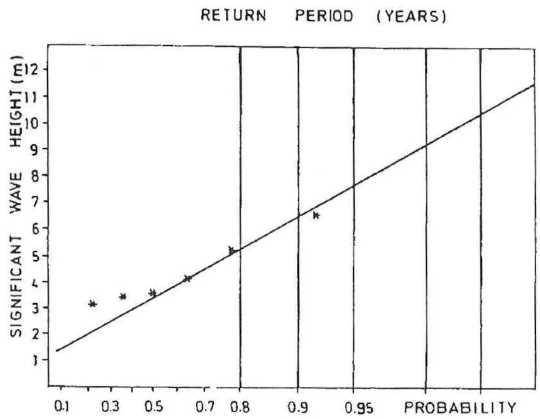


Fig. 3.20. Approximation of cumulative distribution function of extreme values of significant wave heights for December

3.9. CONCLUSIONS

In situations with a strong wind, probability of wave heights higher than 3 meters is about 13% for the Scirocco and about 3% for the Bora. With the Scirocco maximum heights occur in the class 9.5 - 10.0 meters, while with the Bora they occur in the class 7.0 - 7.5 meters. The wave periods generated by the Scirocco are higher than the wave periods generated by the Bora, so that the most frequent Scirocco wave periods occur in the class 5.0 - 7.0 seconds, while the most frequent Bora wave periods occur in the class 4.0 - 6.0 seconds. Monthly and seasonal distribution functions of surface wave heights show distinct seasonal characteristics. This is the result of annual course of the wind speed and direction. In all the seasons there is the greatest probability of wave heights up to 1 meter, however it varies from one season to another. The heights up to 1 meter are most frequent in the summer season (over 90%), while they are the least frequent in autumn (about 55%). The peak wave heights occur in the winter season. Absolute maximum of the wave height in the period of 7 years is 10.2 meters for the Scirocco and 7.2 meters for the Bora respectively.

Evolution of surface wave spectrum also shows significant differences between the situations with Bora and the situations with Scirocco. In the period of the wind speed increase the energy of spectrum maximum shifts toward lower frequencies or higher periods. For the situations with Bora, the period of the wind energy decrease is characterized by shifting of the spectrum maximum toward higher frequencies. On the other hand, with the Scirocco, the surface wave spectrum maximum practically remains on the same frequency.

All the differences between the waves generated by the Bora and the ones generated by the Scirocco can be explained by different fetch dimensions. In the researched area (IKA and IVANA fields), the fetch is several times longer for the Scirocco situations than for the Bora situations.

Two parameter approximations of the real spectra were tested, one of them being the JONSWAP spectrum, and the other its modification made on the basis of the former investigations into the spectral characteristics of the surface waves in the northern Adriatic. Principal characteristic of this modification is taking into account the fact that inclination of the high-frequency part of the surface wave spectrum is -4. From such an assumption dependence follows of the high-frequency energy spectrum on the wind speed. It enables calculation of the surface wave spectra from the known wind direction and speed data. Both parameter presentations relatively well approximate the real spectra. Nevertheless, it should be pointed out that the modified SG spectrum is better than JONSWAP spectrum in approximating the real spectra, and is therefore recommended for use in practice.

An estimate of extreme values of surface wave significant highs was made in such a way that distribution of monthly extreme values was approximated by Gumbel's curve. For the 50-year and 100-year return period for significant heights, values of 10.4 meters and 11.5 meters were obtained respectively. According to the data recorded so far, the obtained values correspond to the expected ones.

3.10. REFERENCES

BLACKMANN, R.B. and J.W. TUKEY, 1958. The measurements of power spectra from the point of view of communications engineering. Dover Publications, New York, 190 pp.

CARTER, D.J.T. and P.G. CHALLENOR, 1980. Estimating return values of environmental parameters. Q.J. Roy. Met. Soc., 107: 259-266.

DARBYSHIRE, J. 1952. The generation of waves by wind. Proc. Roy. Soc. Lond., A215: 299-328.

DRAPER, L. 1966. The analysis and presentation of wave data. Proc. 10th Conf. on coastal Eng., 1, Tokyo, pp. 1-11.

HASSELMANN, K., T.P. BARNETT, E. BOUWS, H. CARLSON, D.E. CARTWRIGHT, K. ENKE, J.A. EWING, H. GIENAPP, D.E. HASSELMANN, P. KRUSEMAN, A. MEERBURG, P. MULLER, D.J. OLBERS, K. RICHTER, W. SELL and H. WALDEN, 1973. Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). Deut. Hydrogr. Zeitschrift A8, 12: 95 pp.

KAHMA, K.K. 1981. On the growth of wind-waves in fetch limited conditions. Rapp. Ser. in Geophysics, Univ. of Helsinki, 15: 1-93.

KITAIGORODSKII, S.A. 1970. Fizika vzaimodeistvija atmosferi i okeana. Gidrometeorologičeskoe izdateljstvo, Leningrad, 283 pp.

NEUMAN, G. 1952. On ocean wave spectra and a new method of forecasting wind-generated sea, Beach erosion board, Tech. Memo. 43 (1952): 42 pp.

PHILLIPS, O.M. 1977. The dynamics of upper ocean. Comb. Univ. Press, 336 pp.

PIERSON, W.J. and L. MOSKOWITZ, 1964. A proposed spectral form for fully developed wind seas based on the similarity of S.A. KITAIGORODSKIJ, J. Geoph. Res., 69: 5181-5190.

SMIRČIĆ, A. 1978. Prilog poznavanju površinskih valova u Jadranskom moru, (in Croatian), Magistarski rad, Sveučilište u Zagrebu, 120 pp.

SMIRČIĆ, A. and M. GAČIĆ, 1982. Istraživanje spektralnih karakteristika površinskih valova uzrokovanih vjetrom na otvorenom dijelu Jadranskog mora, (in Croatian), inter. pub. HI, Split, 80 pp.

SMIRČIĆ, A., M. GAČIĆ and B. KRSTULOVIĆ, 1983. Parametarska aproksimacija spektra površinskih valova sjevernog Jadrana. Dinamika vjetra i strujanja u sjevernom Jadranu - ALPEX rezultati, SHMZ - Beograd i Inst. za oceanografiju i ribarstvo - Split, Spec. pub., 25 pp.

Ekološka studija plinskih polja u sjevernom Jadranu

Površinski valovi

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KRATKI SADRŽAJ

Ovdje se donose rezultati mjerenja površinskih valova iz područja plinskih polja IVANA i IKA iz razdoblja 1978 do 1984 te djelomično iz razdoblja 1985 do 1986. Izračunate su relativne i kumulatine frekvencije visina i perioda valova i raspodjela visina valova po sezonama. Napravljana je statička analiza visina, perioda valova i dužina valova za ekstremne brzine pri karakterističnim vjetrovima buri i jugu. Spektri valova su izračunati iz digitaliziranih zapisa sa parametarskom aproksimacijom. Na kraju su date prognoze ekstremnih vrijednosti značajnih visina valova.