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Assessment of wave impact on hydraulic structures of the Flood Prevention Facility Complex of St. Petersburg obtained from field observations

A.V. Kozhurova*, A.V. Shipilov
"B.E. Vedeneev VNIIG", St. Petersburg, Russia
**E-mail: bagmut_alex@list.ru*

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Abstract. The article describes an attempt to estimate wave parameters from available data of the average and maximum wave heights impacted to hydraulic structures of the FPFC of St. Petersburg obtained from field observations. The methodology was developed to estimate wave heights of the set repeatability during storms, with application of the Monte Carlo method and method of the inverse transform of Smirnov. Convergence of the empirical and model distributions was checked by using the Kolmogorov-Smirnov criterion. Field data analysis shows some storms that took place within the observed period could be characterized by wave heights ($h_{1\,\%}$) exceeding the designed ones.

1. Introduction

The hydraulic structures of Flood Prevent Facility Complex of Saint-Petersburg (FPFC of St. Petersburg) are exposed to different loads and impacts, in particular from water environment: hydrostatic pressure from depth difference in Gulf of Finland and Neva Bay and hydrodynamic pressure caused by wind and ship waves.

Estimation and prediction of actual impacts on hydraulic structures, especially taking account to the problem of climate change, is an important issue, which makes it possible to obtain information needed to ensure reliable and safe operation of hydraulic structures.

According to Russian building code SP 38.13330 [1], for determining loads and impacts on hydraulic structures: for shore protection structures of I and II classes and protective structures of sloping profile of all classes, design repeatability of wave heights is taken no more than 1 % for corresponding design storm.

To investigate the patterns of occurrence, evolution and propagation of wind wave various methods and equipment are used, which make it possible to measure the basic characteristics of surface waves [2–7]. At the FPFC of St. Petersburg, information on the wave impact on the structures can be obtained from the data recorded by the Flood Threat Prevention System (FTPS). The FTPS was designed for flood forecasting and wave impact measurement is not its main function, but this system is records the following data: date and time, sea level in the Baltic system, average wave height, maximum wave height, average wave period, peak period, the period between the intersections of zero-level realizations, energy period, steepness of waves and inhomogeneity of the wave field. The specified parameters of waves are calculated from waveforms obtained by the sensor and transmitted one time per minute to the FTPS. The sensor is measures water pressure and cannot transmit the parameters of single wave or waveforms to the FTPS. It is located at a depth of about 7 meters in water area near the navigation pass S-1 as shown on Fig. 1. The FTPS also has other sensors near the navigation pass S-2 and sluices V-1 and V-5, but in this article is analyzed only data from sensor near the navigation pass S-1.

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Figure 1. FTPS sensor location scheme.

The relevance of investigation of storm waves is justified by many authors [8–10]. The wave conditions in the Baltic Sea were considered in [11–14]. Theoretical estimates of extreme waves and wave conditions of the Gulf of Finland are presented in [15–16]. It is also noted that the season of the most powerful wave activity of the Baltic Sea is often not interconnected with the period of the strongest winds [17].

This article represents an attempt to estimate wave parameters from available data of the average and maximum wave heights affecting the hydraulic structures of the FPFC of St. Petersburg obtained during field observations, and to determine the calculated wind wave height with repeatability 1 % during the observed storms for their further comparison with the values accepted in project. For this purpose authors fulfilled the analysis of the series of observations recorded by the FTPS gauge located at the structures of navigation pass S-1. The data used in this article were provided by State Owned Enterprise “Directorate of FPFC of the Saint Petersburg Ministry of Construction Industry, Housing and Utilities Sector of Russian Federation” from database of FTPS.

Authors could not find the articles are describing methods of statistical estimation of wave parameters during the storm from the average and maximum wave heights in open publications, and for with purpose a special methodology has been developed.

2. Methods

To determine the wave height of 1 % of repeatability ($h_{1\%}$) during the storm and to compare the actual wave impact on the hydraulic structures with the designed one, it is necessary to have statistical data of wave heights, or a known empirical function of their distribution. Wave characteristics should be recorded using available waveforms and contain a record of at least 100 waves following each other continuously [18]. FTPS sensors calculate the average value of wave heights in the interval of 1 minute, which does not allow explicitly evaluate the law of distribution of wave heights and as a consequence to evaluate their repeatability.

To solve this problem and obtain data needed to analyze the impact of wind waves, a special methodology has been developed, the scheme of which is shown on Fig. 2.

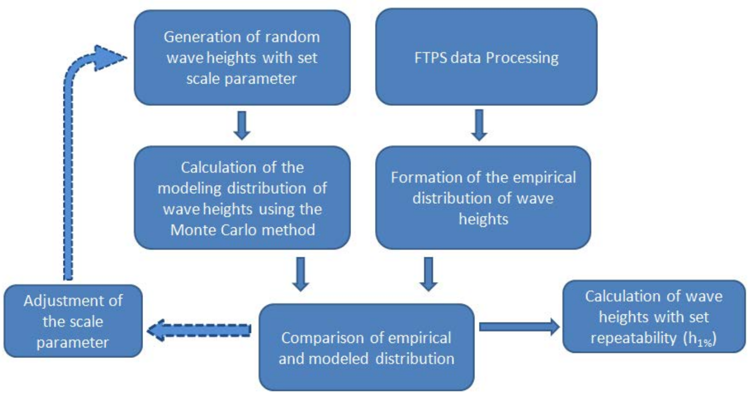


Figure 2. Methodology used to analyze the impact of wind waves.

According to the methodology, the FTPS data were processed with the next forming of the empirical distribution of the averaged wave heights observed during the selected storm.

Next, random wave heights were generated and a model distribution of their averaged values was calculated using the Monte Carlo method, with following assumptions:

1) During a storm, the distribution of the height of a single wave obeys the Rayleigh law;

2) The scale factor in the Rayleigh distribution during the storm remains unchanged.

To calculate a modeled distribution, a special algorithm has been developed that makes it possible to simulate data obtained by the gauge FTPS during a storm, taking into account the assumptions made above. During the execution of the algorithm, 20 unit waves were generated, which approximately corresponds to an interval of 1 minute for a wave period of 3 seconds, and then their averaging was performed.

The generation of random variables of a given distribution was carried out by the method of inverse transform developed by N.V. Smirnov. Assuming that the height of the wind waves obeys the Rayleigh distribution, the generation of a random variable was performed according to the formula:

$$x_i = a \cdot \sqrt{-2 \cdot \ln r_i} \ ,$$

where x_i is a random variable having a Rayleigh distribution, r_i is a random variable having a uniform distribution in the range from 0 to 1, a is a scale parameter in the Rayleigh distribution.

By generating and evaluating 100000 averaged quantities, a simulated distribution function was constructed which was compared with the empirical one.

The scale parameter in the Rayleigh distribution (a) was selected so that the distribution obtained by modeling was most consistent with the empirical one. Probability density functions were reduced to one scale for comparison, based on the condition of the probability density function area is equal to the one.

To generate single random wave height, a cryptographically strong pseudorandom number generator was used.

After obtaining good convergence of the empirical and model distributions, their consistent was checked by using the Kolmogorov-Smirnov criterion. For storms with empirical distribution of averaged wave heights consistent with the model one, wave heights $h_{1\%}$ were calculated and the obtained values were compared with the design ones.

During the processing of empirical data taken by the measuring system was excluded data which at least one measure has missed. Measurement errors were also not taken into account in the analysis.

3. Results and Discussion

To estimate the wave heights, the periods of storm impacts has been distinguished.

In regulatory documents, for example, RD 52.10.865-2017 [19], a storm is defined as a period of time with wave heights above a given level. In Russian State Standard GOST R 55615.3-2013 [20] it is described as a condition in the sea, under which the wind speed averaged over 10 minutes is 15 m/sec or more.

In this paper, a storm has been determined as a period of time lasting more than 100 minutes, during which the wind had an average maximum speed, exceeds 15 m/sec within 10-minute period.

According to the methodology described above the data array was processed, from November 22, 2011 to December 31, 2019. In the considered period several months were skipped: in 2016 – a total of 2 months, in 2019 – 6 months.

The time intervals of the storm impacts obtained after processing the observation series of the FTPS gauge located at the structures of navigation pass S-1 are presented in Table 1.

Table 1. Time intervals of storm impacts on the structures during 2011–2019.

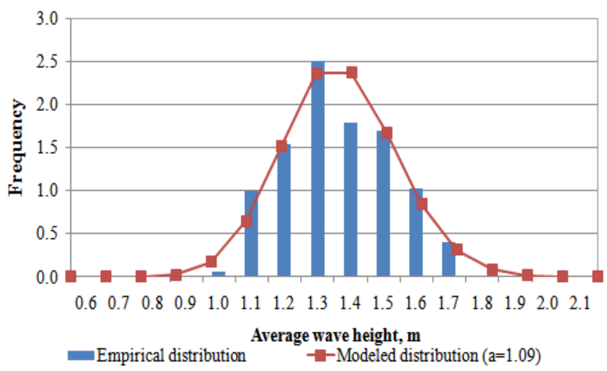
Storm's №	Beginning		End		Interval of observation, min	Wind direction*, degree	Average of maximum wind speed, m/sec
	Date	Time	Date	Time			
1	28.11.2011	00:11	28.11.2011	15:20	909	230-300	21.0
2	26.12.2011	08:29	26.12.2011	19:38	668	239-276	23.0
3	27.12.2011	06:11	27.12.2011	10:56	285	237-287	26.0
4	27.12.2011	12:47	28.12.2011	13:09	1450	259-292	25.0
5	12.05.2012	07:32	12.05.2012	10:56	204	261-270	17.0
6	17.06.2012	19:30	18.06.2012	06:53	506	197-261	16.0
7	19.06.2012	17:56	19.06.2012	19:51	114	237-257	16.0
8	20.06.2012	05:25	20.06.2012	07:36	131	260-268	19.0
9	23.08.2012	16:03	23.08.2012	20:55	289	248-286	18.0
10	06.11.2012	21:26	07.11.2012	02:51	324	253-283	18.0
11	07.11.2012	18:32	07.11.2012	23:15	282	213-292	17.0
12	12.11.2012	17:07	12.11.2012	20:10	183	226-239	17.0
13	12.11.2012	20:42	12.11.2012	23:34	172	255-270	17.0
14	17.07.2013	07:59	17.07.2013	16:29	510	241-259	17.0
15	15.08.2013	13:07	15.08.2013	20:12	425	236-250	20.0
16	15.08.2013	20:36	16.08.2013	00:00	201	258-272	20.0
17	19.10.2013	10:00	19.10.2013	12:44	160	265-283	21.0
18	19.10.2013	15:03	19.10.2013	18:31	201	268-302	17.0
19	17.11.2013	00:55	17.11.2013	08:45	465	233-297	24.0
20	17.11.2013	08:47	17.11.2013	15:24	397	260-285	24.0
21	27.11.2013	20:37	27.11.2013	22:29	100	232-257	18.0
22	28.11.2013	02:03	28.11.2013	07:03	276	259-272	19.0
23	28.11.2013	11:01	28.11.2013	17:41	387	255-286	18.0
24	12.12.2013	22:03	13.12.2013	13:46	943	217-325	26.0
25	22.12.2013	02:25	22.12.2013	04:07	102	235-238	16.0
26	08.03.2014	12:04	08.03.2014	19:50	387	222-248	18.0
27	05.04.2014	09:48	05.04.2014	15:40	347	236-245	20.0
28	05.04.2014	17:48	05.04.2014	22:10	254	246-253	21.0
29	03.12.2014	21:41	03.12.2014	23:48	127	227-234	18.0
30	03.12.2014	23:49	04.12.2014	05:12	323	234-251	18.0
31	13.12.2014	16:45	13.12.2014	19:46	181	251-265	22.0
32	13.12.2014	19:47	13.12.2014	21:47	120	247-267	22.0
33	10.04.2015	01:06	10.04.2015	04:14	188	249-267	16.0
34	10.04.2015	20:24	10.04.2015	22:09	105	242-262	18.0
35	22.04.2015	14:31	22.04.2015	16:48	122	256-265	18.0
36	04.06.2015	06:32	04.06.2015	20:35	810	236-262	18.0
37	11.06.2015	14:01	11.06.2015	16:08	127	256-259	15.0
38	22.07.2015	19:03	22.07.2015	22:43	219	259-275	17.0
39	02.08.2015	03:38	02.08.2015	05:38	113	251-262	15.0
40	06.12.2015	06:07	07.12.2015	03:15	1257	210-270	25.0
41	07.12.2015	04:17	07.12.2015	12:31	486	252-270	19.0
42	07.12.2015	12:32	07.12.2015	20:10	452	266-301	19.0
43	08.12.2015	02:45	08.12.2015	10:17	432	276-288	16.0
44	09.06.2016	06:27	09.06.2016	15:03	515	271-289	20.0
45	05.07.2016	01:35	05.07.2016	14:37	782	262-300	22.0
46	05.07.2016	14:47	06.07.2016	16:41	1494	270-288	22.0
47	02.06.2017	08:15	02.06.2017	14:20	365	279-302	18.0
48	21.06.2017	09:31	21.06.2017	16:58	427	263-292	17.0
49	27.06.2017	10:20	27.06.2017	20:10	571	257-271	17.0
50	18.10.2017	02:41	18.10.2017	04:39	118	252-256	16.0

Storm's №	Beginning		End		Interval of observation, min	Wind direction*, degree	Average of maximum wind speed, m/sec
	Date	Time	Date	Time			
51	13.12.2017	11:13	13.12.2017	13:52	139	250-267	17.0
52	07.01.2018	7:31	07.01.2018	18:45	670	269-291	18.0
53	08.01.2018	0:03	08.01.2018	4:14	249	261-272	18.0
54	08.01.2018	4:15	08.01.2018	7:30	195	270-278	18.0
55	05.06.2018	2:56	05.06.2018	10:42	466	279-318	18.0
56	19.06.2018	20:01	19.06.2018	22:42	142	236-257	21.0
57	20.06.2018	11:25	20.06.2018	19:24	373	250-259	19.0
58	29.06.2018	16:06	29.06.2018	19:11	183	223-279	17.0
59	06.08.2018	13:54	06.08.2018	16:24	149	240-269	16.0
60	21.08.2018	3:44	21.08.2018	5:38	114	273-315	22.0
61	12.09.2018	7:55	12.09.2018	19:23	607	217-245	23.0
62	13.09.2018	12:20	13.09.2018	15:24	184	250-259	19.0
63	17.09.2018	22:27	18.09.2018	2:45	258	261-293	18.0
64	26.09.2018	14:32	27.09.2018	21:42	1760	186-288	22.0
65	22.11.2018	2:12	22.11.2018	4:18	123	264-287	18.0
66	14.09.2019	11:23	14.09.2019	16:24	286	278-291	16.0
67	15.09.2019	20:13	16.09.2019	01:34	319	235-295	20.0
68	16.09.2019	07:43	16.09.2019	13:22	337	253-296	16.0
69	01.10.2019	10:17	01.10.2019	17:19	419	237-265	22.0
70	12.10.2019	14:58	12.10.2019	18:15	194	255-266	19.0
71	12.10.2019	18:50	12.10.2019	22:55	245	272-301	19.0
72	22.10.2019	20:12	23.10.2019	01:58	347	246-259	20.0
73	23.10.2019	01:59	23.10.2019	07:28	329	252-274	20.0
74	25.10.2019	22:57	26.10.2019	12:55	681	231-257	20.0
75	26.10.2019	20:35	26.10.2019	22:19	104	240-268	20.0
76	05.12.2019	18:56	06.12.2019	00:02	306	232-244	19.0
77	06.12.2019	00:03	06.12.2019	04:51	288	228-234	19.0
78	18.12.2019	23:31	19.12.2019	05:41	325	266-301	27.0
79	19.12.2019	07:14	19.12.2019	09:45	150	285-295	16.0
80	30.12.2019	16:16	30.12.2019	18:12	115	247-254	16.0

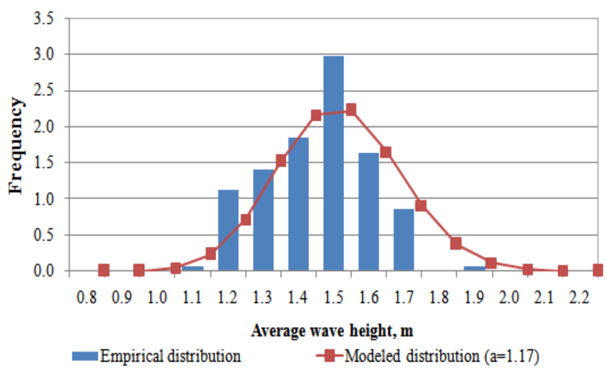
Note: the north direction of the wind is taken as zero, the positive direction of the angle coincides with the clockwise direction.

Based on the accepted conditions for determining the storm, those that were less than 100 minutes were excluded from the found intervals. Also, occurring only storms in the western direction of the wind (direction from 230-315°) were considered, since due to conditions of location of structures in other directions, the wave way length is not enough to form a significant height.

The figures below (Fig. 3) show examples of the modeled and empirical distributions using the above-mentioned methodology.



Storm № 10



Storm № 22

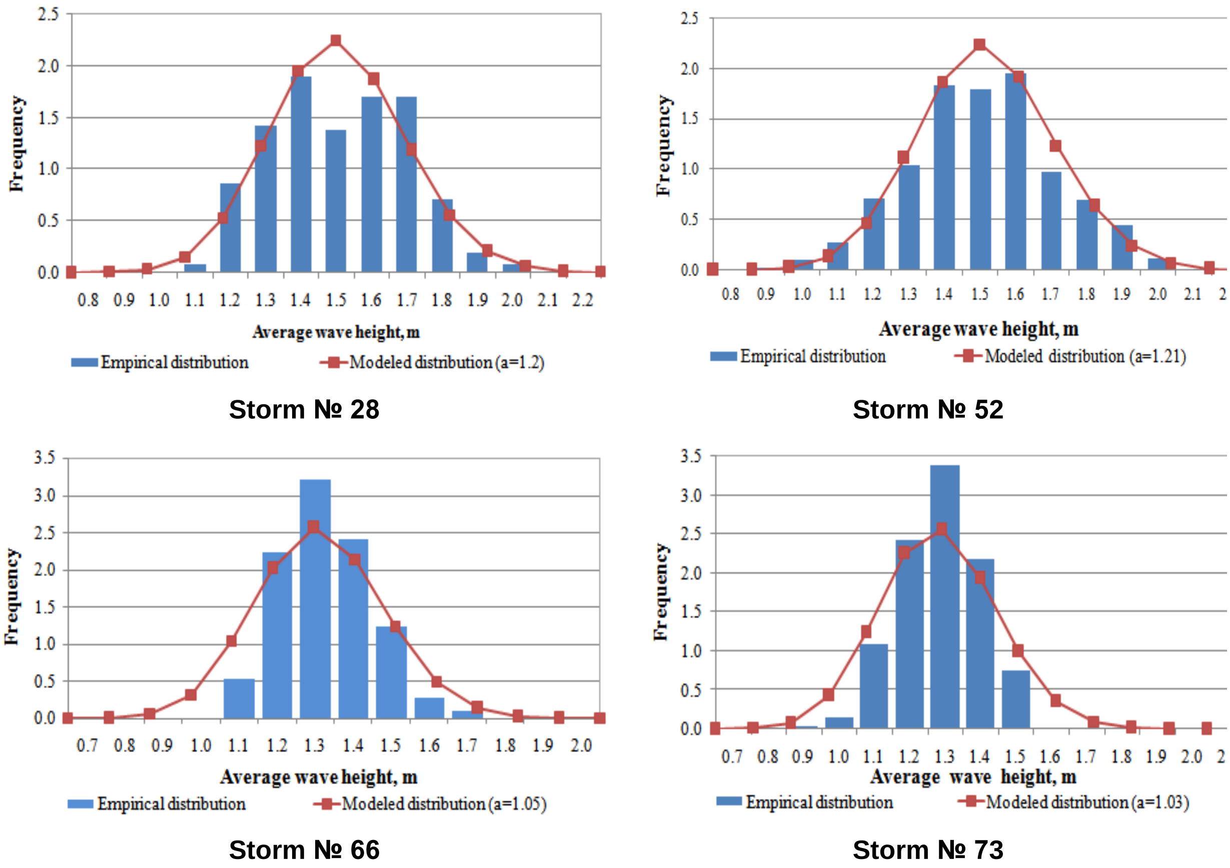


Figure 3. Examples of modeling and empirical distributions.

For the obtained intervals of the storms, the consistency of model and empirical distributions has been checked using the Kolmogorov-Smirnov criterion. Statistics of the criterion D_n was determined by the formula:

$$D_n = \sup_x \left| F_n(x) - F(x) \right|,$$

where $F_n(x)$ is the empirical probability distribution function, $F(x)$ is the modeled probability distribution function.

The critical value of the statistics $D_n{*}$ was calculated by the method described in [21].

The calculation of the wave heights of 1 % repeatability ($h_{1\%}$) was performed according to the formula:

$$h_{1\%} = a \cdot \sqrt{-2 \cdot \ln(0.01)} \,,$$

where a is a scale parameter in the Rayleigh distribution.

The corresponding calculated wave heights of 1 % repeatability ($h_{1\%}$), the magnitude of the obtained scale parameters in the Rayleigh distribution, and the values of the measured maximum waves observed in a storm, for storms in which the empirical distribution was consistent with the modeled, are shown in Table 2.

Table 2. Parameters of storms satisfying to condition of consistency of modeled and empirical distribution.

№	Storm's №	Number of observations	Scale parameter, α	H_{max}, м	$h_{1\%}$, м	Kolmogorov-Smirnov criterion	D_n	D_n^*
1	5	204	0.79	1.9	2.4	0.65	0.046	0.105
2	9	289	0.97	2.3	2.9	0.90	0.053	0.088
3	10	324	1.09	2.6	3.3	0.70	0.039	0.084
4	11	282	1.22	3.0	**3.7**	1.32	0.079	0.090
5	12	183	0.95	2.2	2.9	0.84	0.061	0.108
6	13	172	1.22	2.8	**3.7**	1.18	0.090	0.115
7	14	510	0.79	2.0	2.4	1.30	0.058	0.067
8	16	201	0.60	1.3	1.8	1.25	0.088	0.105
9	18	201	0.74	1.8	2.2	1.03	0.071	0.104
10	19	465	0.95	2.2	2.9	0.92	0.043	0.070
11	21	100	1.12	2.4	**3.4**	1.46	0.138	0.142
12	22	276	1.17	2.8	**3.6**	0.85	0.049	0.087
13	23	387	0.92	2.1	2.8	1.47	0.074	0.075
14	25	102	0.65	1.4	2.0	0.81	0.080	0.148
15	28	254	1.20	3.0	**3.6**	1.05	0.065	0.093
16	29	127	0.85	2.0	2.6	1.33	0.118	0.133
17	31	181	1.52	3.6	**4.6**	0.55	0.041	0.112
18	32	120	1.10	2.9	3.3	1.34	0.122	0.137
19	34	105	0.68	1.7	2.1	0.38	0.037	0.146
20	35	122	0.67	1.6	2.0	0.64	0.055	0.128
21	37	127	0.73	1.7	2.2	0.67	0.059	0.133
22	38	219	0.73	1.8	2.2	1.46	0.099	0.101
23	39	113	0.84	1.9	2.5	0.95	0.087	0.137
24	40	1257	0.97	3.0	2.9	0.80	0.023	0.042
25	41	486	1.20	2.8	**3.6**	0.88	0.043	0.073
26	45	782	1.05	2.7	3.2	1.04	0.037	0.054
27	51	139	0.76	2.1	2.2	1.30	0.103	0.119
28	52	670	1.21	2.9	**3.7**	1.28	0.049	0.058
29	53	249	1.46	3.2	**4.4**	1.12	0.071	0.095
30	54	195	0.86	2.4	2.6	1.38	0.099	0.108
31	55	466	0.82	2.1	2.5	0.48	0.022	0.070
32	56	142	0.61	1.6	1.9	1.24	0.098	0.118
33	57	373	0.95	2.1	2.9	1.40	0.064	0.069
34	60	114	0.47	1.4	1.4	1.08	0.101	0.140
35	62	184	0.92	2.4	2.8	1.34	0.099	0.111
36	66	286	1.05	2.6	3.2	1.48	0.085	0.087
37	67	319	1.17	3.0	**3.6**	1.49	0.083	0.084
38	68	337	0.96	2.1	2.9	1.46	0.079	0.082
39	71	245	0.86	2.7	2.6	0.92	0.059	0.096
40	73	329	1.03	2.3	3.1	1.29	0.071	0.083
41	78	325	1.61	3.5	**4.9**	1.14	0.059	0.078
42	80	115	0.71	1.7	2.2	0.26	0.024	0.139

Note: H_{max} is the maximum of wave height recorded in the interval of 1 minute recorded by the FTPS gauge during the storm.

In addition, as a check, for the storms shown in Table 2, the distribution of the maximum waves recorded in the interval of 1 minute has been simulated. The obtained modal values of the distribution of the heights of the maximum waves were close to the values observed during the storm with an accuracy of 0.1 m. This also confirms the correctness of the chosen methodology.

The data presented in Table 2 shows that the calculated values of wave heights for 11 storms impacting on the structures of the FPFC of St. Petersburg during the operational period exceed the design value of the load of 0.1 % repeatability – 3.37 m at a wind speed of up to 22 m/sec, which is less than the declared design value of 27 m/sec. Also, several storms exceeded the load value of 0.01 % repeatability at a wind speed of 22–27 m/sec. Design values are presented in Table 3.

Table 3. Parameters of extreme waves from the Gulf of Finland for the main combination of loads and impacts during normal operation of structures of navigation pass S-1.

Kronstadt Level		Parameters			
Value, m in the Baltic system	Repeatability, %	Wind speed and direction	Wave height $h_{1\%}$, m	Wave period $\overline{\tau}$, sec	Wave length $\overline{\lambda}$, m
0.00	–	15 m/sec, West	1.86	4.2	10.2
4.55	0.1	27 m/sec, West	3.37	5.9	18.5
5.15	0.01	27 m/sec, West	4.15	5.9	19.4

Since the calculated wave heights of 1 % repeatability was obtained by the indirect method, and not by direct observation of the heights of individual waves obtained from the waveforms, the above results require further investigation.

4. Conclusions

1. Authors could not find the articles are describing methods of statistical estimation of wave parameters during the storm from the average and maximum wave heights in open publications, and for with purpose a special methodology has been developed.

2. The developed methodology for estimating wave heights shows satisfactory convergence with field observations, although it requires verification with the data obtained with the use of other methods.

3. Some of the obtained wave heights of 1 % repeatability for the considered period exceed the maximum design values. The above-mentioned methodology for determining the wave heights of 1 % repeatability is indirect, based on the solution of an inverse problem, and the values obtained from it should be considered indicative, requiring further detailed study.

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Contacts:

Alexandra Kozhurova, bagmut_alex@list.ru
Aleksandr Shipilov, a.shipilov@yahoo.com