A PROJECT OF CONCRETE STABILIZED SPAR BUOY FOR MONITORING NEAR-SHORE ENVIRONEMENT

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ABSTRACT. Feasibility study of a long-lived autonomous sea observatory on the basis of a stabilized spar buoy is presented. The buoy design is developed to sustain harsh weather and hydrodynamic conditions of near-shore of the North-Eastern Black Sea with expected life-time over 10 years. It has the following dimensions: diameter 2.4 m, total length 45 meters, prestressed concrete bearing structure 33 m, floating draft 30 m, 3 m above-water concrete body, 12 m steel mast, dry weight about 120 tonnes. The buoy is equipped with mooring anchors and three submerged flotages for its stabilization and minimization of an observational noise of in situ and remote measurements.

To perform the design testing, elaborate technical requirements and adopt particular technological and logistical solutions numerical simulations are conducted. Strength and durability of the buoy are assessed primarily through random response analysis of its stress-strain state under irregular wind-wave conditions with requirements of the actual standards and codes also taken into consideration. Characteristics of near-shore environment, in particular, typical and extreme wind-wave conditions are specified for a site of the Field Research Facility of the Southern Branch of the P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences (Gelendzhik Bay, Russia) using historical data and theoretical models of wind-wave growth in the near-shore.

The low-cost concrete buoys of the proposed design can be used both as autonomous sea stations and as units of networks for marine studies and monitoring sea environment. Dynamical characteristics of the buoy and special mooring system ensure high-precision measurements as well as possible applications in telecommunication, maritime safety etc.

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INTRODUCTION.

Methods and tools of monitoring and exploitation of the sea for the last decades shows clear tendency to autonomous, multipurpose and low-cost solutions. Development of long-lived sea platforms that are able to carry the high-technology instrumentation, protect it from natural exposure, supply energy, provide data storage and reliable communication with data centers are important issues of these solutions.

In this work we present a project of a stationary research platform for near-shore.

This platform is seen as a universal structure for sea environment research and monitoring as well as for other problems of marine safety, including commercial communication networks in the sea nearshore.

Two key features of the proposed autonomous long-lived (10 years minimum) sea observatory should be emphasized. First, the solution of an anchored spar buoy is aimed at comfortable conditions for on-board instrumentation providing accurate measurements in boundary layer atmosphere-ocean. Secondly, the low cost of the prestressed concrete construction and the corresponding logistical solutions give prospects for deployment of these observational platforms in different areas of the World Ocean and in enclosed basins. Evidently, the above advantages should be paid by thorough analysis of different aspects of the buoy construction, deployment and operation. In this work we present this analysis for specific conditions of the North-Eastern Black Sea nearshore.

In Sect.1 we present an overview of wind sea conditions at the Field Research Facility of the Southern Branch of the P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences. The experimental buoy will be deployed near the Gelendzik Bay approximately 5 nautical miles offshore and included into the existent network of scientific instrumentation.

Sect.2 is devoted to analysis of behavior of the buoy as a rigid body. The floating research platform should minimize effects of currents, waves and winds for high performance of the on-board instrumentation. Amplitude-frequency characteristics of the buoy are estimated for local conditions of the experimental site.

Strength and durability of the buoy under irregular sea-state conditions were studied numerically. Sect.3 presents these results and recommendations in accordance with requirements of the actual standards and codes. These requirements essentially determine the choice of the structural material, technology of the buoy manufacturing, transportation and deployment.

Discussion summarizes results of the study in the context of feasibility of the project.

1. THE NORTH-EASTERN BLACK SEA NEAR-SHORE CONDITIONS

The North-Eastern coast of the Black Sea is characterized by specific conditions of winds, wave regimes and bottom topography. Severe winds are essentially local being determined by orographic features of the coast. The well-known phenomenon of the Novorossiysk bora proposes an example of extreme event when at mean speed about 20 m/s wind gusts can exceed 60 m/s (the maximum 80m/s has been fixed in 1928 at Markhotsky Pass). Air temperature can fall by more than 20 degrees. The bora occurs up to 40 days annually and affects coastal waters 10-15 km offshore. These conditions should be taken into account for a marine structure with respect to its amplitude-frequency response and during analysis of the structure dynamics and durability.

The difficulty of analysis of wind-wave conditions in our case is in quite scarce meteorological data in this region and in essential spatial intermittency of the events when wind field represents a number of jets where the wind (and sea waves) reach their extremes (Gavrikov, Ivanov, 2015). Accurate forecasting of such events is quite difficult within standard approaches.

Analysis of marine structure durability requires a number of parameters of wind and wave fields. In addition to extreme and mean-over-time parameters (e.g. wind speed or wave height) statistical features should be considered for the structure that is affected by fluctuating loads of wind and waves. In this section we sketch an approach that allows us for specifying the amplitude-frequency characteristics and their possible extrapolation for the expected extreme conditions in the area.

Data of a wave rider operated near the future experimental site have been used as a basis for studies of the buoy dynamics and durability. The Datawell buoy was set at 7 km offshore near the Gelendzik Bay within the NATO TU-WAWES Project. Wave data cover the period 1996-2003 (totally 56 months). Bulk parameters of sea waves, wave heights (mean and maximal over standard time window H_{avg} and H_{max}, 10% and 30% probability $H_{1/10}$, $H_{1/3}$), wave periods (similar to wave height) and mean direction provide approximately 160000 records for the years of measurements. These parameters have been used to specify typical regimes of wind-sea forcing at the experimental site. As far as reliable measurements of near surface wind are absent the analysis of the data has been carried out within the recent wind-free paradigm (Zakharov, Badulin, Hwang & Caulliez, 2015). The outcome of such analysis is an estimate of pairs of the key wave parameters, significant wave height and wave periods, as an input for further amplitude-frequency response analysis of the spar buoy.

Fig.1 shows the experimental site, 7 km off the Gelendzik Bay mouth and 31 km from the Myskhako Point. Probability of wave direction is illustrated by Fig.2 (direction from, i.e. 90 degrees - waves running from the East). Three dominant regimes of wind waves are clearly seen. More than 10% cases are associated with the North-Eastern offshore direction (45^{o}) providing an example of the fetch-limited development of wind waves running perpendicularly to the almost straight coast. The severe events of the Novorossiysk bora mentioned above can occur for these directions when local wind speed exceed 30m/s. The South-East direction gives approximately 15% of cases when waves propagate along-shore. More than 30% of observations can be related to the North-Western sector (appr. 255^{o}). Wind speed at the measurement site can differ dramatically from the one measured by the nearest meteorological station in the Geledzhik airport. Results of simulations within the WRF-ARW model (Weather Research and Forecast Model) have been used for estimates of extreme winds when modeling wind loads on the structure.

The amplitude-frequency characteristics of the wind field have been assessed within the wind-free approach (Zakharov et al. 2015) for the dominant regimes outlined in fig.2. The wind-free invariant for growing wind waves can be written as follows:

$$\mu^4 \nu = \alpha_0^3 . \tag{1}$$

Here $\nu=2k_p x$ - dimensionless fetch in number of instantly measured wavelengths, $\alpha_0=0.7$ − a counterpart of the Kolmogorov-Zakharov constant of the theory of weak turbulence (Zakharov, 2010). Correspondence to Eq.(1) is found to be a good indicator of wind wave regimes in the nearshore when wave fetch is specified by coast lines of the Gelendzhik Mouth (wave direction 45^{o}) or Myskhako Point (255^{o}).

Fig.1. The location of Datawell buoy (1996-2003) at the experimental site of the Southern Branch of the P.P. Shirshov Institute of Oceanology

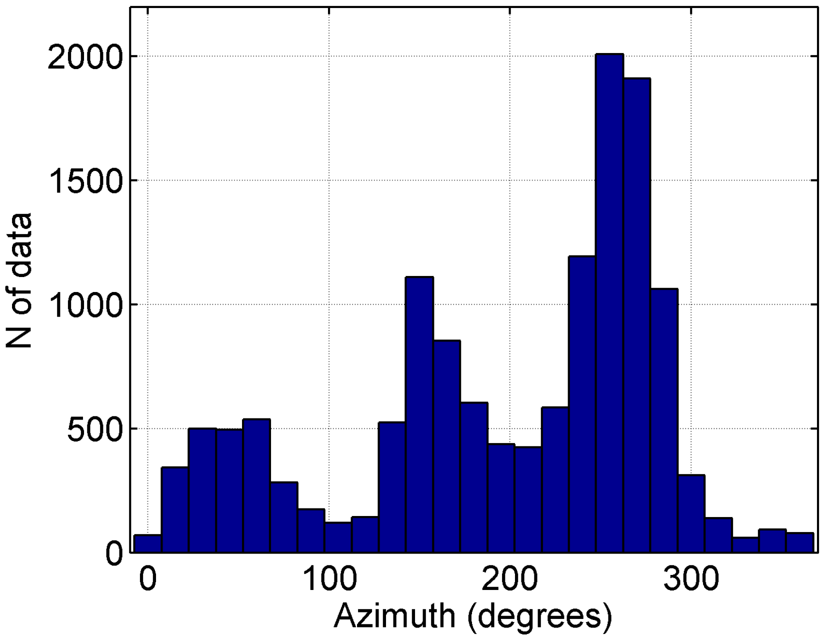

Fig.2. Number of measurements of the Datawell buoy (1996-2003) as function of wave direction.

Fig.3 shows reference amplitude-frequency regimes for the first case (direction 45°, the Geledzhik Mouth). Red lines trace conditions of constant wave slope μ (see eq.1) defined in terms of spectral peak period T_p and significant wave height H_s as follows

$$\mu = \frac{\pi^2 H_s}{g T_p^2} . \qquad (2)$$

High steepness μ=0.1 is shown by red line as a reference one for a rough wind sea while the lower value μ=0.04 is close to the Pierson-Moskowitz (1964) criterium of a fully developed (mature) wind sea. Blue line in fig.3 corresponds to the wind-free invariant (1) that prescribes dependence of wave steepness on dimensionless fetch expressed in instantaneous wavelength. The measurements with wave height above 0.5 meters are fall into a gusset limited by the invariant of fetch-limited growth (1) and wave steepness slightly above μ*=0.1.* A background of relatively low waves (μ < 40 cm) covers a wide range of wave steepness and can be related to daily breeze in this area.

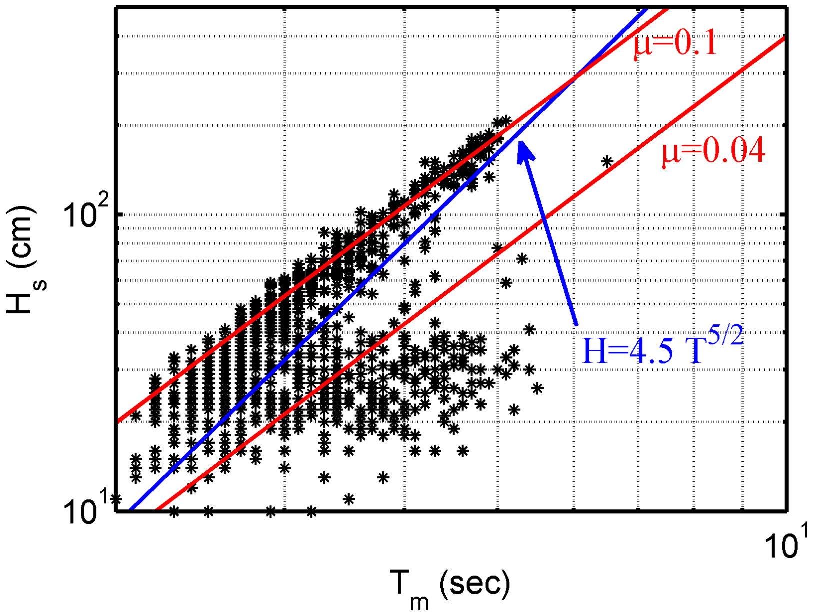

Fig.3. Wave-height-period plots for South-Eastern (top) and North-Eastern wave directions.

The presented approach allows us for assessment of reference parameters as an input for further analysis of wave loads. The spectral distributions for the analysis can be specified by widely used parameterizations of waves spectra (e.g. Hasselmann et al., 1973).

2. PRELIMINARY ESTIMATES OF THE BUOY PARAMETERS

Preliminary estimates of the buoy size and weight can be made within the simplest models of the floating body. The concrete as a key construction material of the buoy has natural restrictions for its use in floating marine structure. Rather high density (appr. 2400 kg/m^3) and relatively low strength as compared to steel require an accurate consideration of size and weight characteristics of the concrete structure.

2.1. Static of the buoy: buoyancy to weight aspect

From the very beginning we fix the basic geometry of the proposed buoy as a cylindrical body with relatively thin shell to provide sufficient buoyancy to carry an instrumentation and to provide high stabilization of the structure under effect of winds and waves. Within the simple geometry the only dimensionless ratio of the shell thickness Δ to the buoy radius R determines the buoyancy capacity. The condition $k=\Delta/R<0.236$ ensures positive buoyancy. With minimal shell thickness Δ_{min}=12 cm dictated by technological regulations the spar buoy diameter should be greater than 101.7cm. The upper limit of the radius can be limited by the Russian Route Code that restricts transportation of articles greater than 2.5 meters width without special permission. We accepted the radius of the proposed structure R=1.2 meter for the further discussion as a default one.

In order to assure the buoy stabilization and comfortable conditions for instrumentation (see the next section) the size of the concrete body has been fixed as an underwater length H_B=30 m and the above-water concrete section H_A=3 m (see Fig.4). For the default buoy radius R=1.2 m and the shell thickness Δ=20 cm ($k=\Delta/R=0.166$) one has gross payload Q_B=37.8 tonnes. The minimal thickness of the buoy shell Δ_{min}=12 cm and the same ratio $k=\Delta/R=0.166$ provide the gross payload Q_B=15 tonnes. With the water ballast of 10 meters height for the buoy vertical stabilization the above two examples provide net payloads 6.2 and 2.7 tonnes correspondingly.

2.2. Dynamics of the buoy: the buoy stabilization

The issue of the buoy stabilization is a key one in the project. Preliminary estimates of this quality can be made for a buoy as a rigid floating body under action of the gravity and buoyancy forces. Balance of the forces and their moments with the added liquid mass taken into account provide equations of infinitesimal oscillations and the corresponding eigen frequencies of transitional (up-and-down) and rotational (tilting) motions. For the default R=1.2 m, H_B=30 m, H_A=3 m and shell thickness Δ=15 cm (the buoy weight m_b=136 tonnes) the transitional eigen frequency $f_{tr}=0.088$ Hz and the rotational one f_{rot}=0.055 Hz appear to be acceptable for the conditions of the Black Sea nearshore where wave periods are generally lower than 8 seconds. The attenuation of vertical motion by factor 15 for the buoy with this parameters can be enhanced by installing damping flaps.

2.3. Key parameters of the stabilized concrete spare buoy

The above analysis leads us to the following design of the concrete spar buoy for the condition of the North-Eastern Black Sea nearshore. The key parameters of the buoy are based both on quantitative analysis of the buoy behavior and on other aspects of its manufacturing, transportation, deployment and exploitation:

1. Overall length 45 meters includes the concrete body and steelwork part for installing instrumentation;
2. Subsurface part with draft 30 meters and diameter 2.4 meters is acceptable for the Black Sea nearshore with rather deep shelf zone. The depth of the experimental site is in the range 80-100 meters;
3. Surface part: with concrete body height 3 m and steel mast of 12 m are made for comfortable installation of instrumentation and maintenance of the platform;
4. Concrete shell thickness 0.15 m is sufficient for the platform strength and lifetime for 10 years;
5. Dry weight approximately 120 tonnes allows for the buoy deployment with available research vessels of the South Branch of the P.P.Shirshov Institute;

6. Buoyancy of the empty structure 16 tonnes is sufficient for installation necessary equipment and ballast;
7. Distance between centers of mass and buoyancy 3 m guarantees stabilization of the buoy for typical conditions of the Black Sea near-shore
8. Ballast water column height ≈ 10 m is needed for easy transportation of the buoy to the deployment site. Water pumps are used ballasting and tuning buoyancy for better performance of the buoy;
9. Eigen frequencies of the buoy motion (heave 0.09 Hz, roll 0.05 Hz) guarantee stabilization of the buoy under typical wind sea conditions;
10. Damping coefficient at heave resonance frequency about 15 (ratio of vertical buoy displacement to significant wave height) can be increased by using special flaps;
11. Maximal roll angle at resonance frequency ≈ 5^0 ensures stabilization of scientific equipment and telecommunication systems;
12. Eigen frequencies of deformation (with 360 kg load at the mast):
5.726 Гц; 11.576 Гц; 17.615 Гц; 19.336 Гц; 22.548 Гц

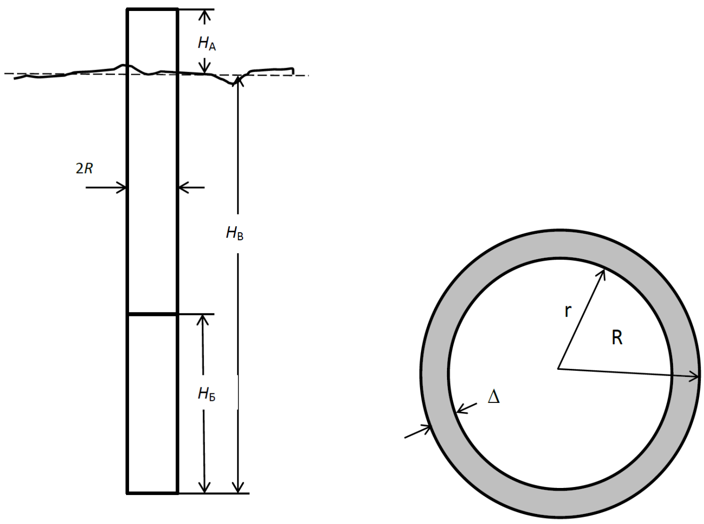

Fig. 4. The project of the concrete stabilized spar buoy.

3. STRENGTH AND DURABILITY ANALYSIS

3.1. Strength and durability analysis

Strength and durability analysis of the concrete stabilized spar buoy was performed into several steps. As the first step natural frequencies were calculated with the water added mass taken into consideration to assess the feasibility of the project with respect to wave forcing response and possible resonance. It was found that the structure's first natural frequencies $f_{1,2}$=5.726 Hz and $f_{3,4}$=11.576 Hz are much higher than frequencies of surface gravity waves, so the resonant excitation is not expected.

After natural frequency analysis we proceeded with the project design. Waves forcing is of primary importance for such structures (small exposed surface ensures relatively low wind loads on the mast). Moreover, this forcing produces alternating loads in the buoy body. Since tension resistance of concrete is more than one order of magnitude less than compression resistance the pre-stressed concrete body of the structure is seen as unavoidable solution to guarantee the structure health for the long period of its exploitation in the sea.

Since requirements of building codes do not allow for cracking of concrete structures of such type, two strength and durability conditions should be satisfied:

a) compressive stresses due to concrete pre-stress and external loads should not exceed concrete compression resistance;
b) tensile stresses due to external forces should exceed the concrete pre-stress magnitude.

In our case the concrete structure health is determined by a number of factors including heavily nonlinear processes of wave loading. Hence it is very difficult to accurately identify which of the possible loading cases will be the worst one. Seven different loading scenarios have been defined for accurate accounting this feature in the structure strength analysis (see also Table 1):

1. Active phase of local storms (time intervals 3 hours);
2. Standard storms (7 hours);
3. Daily loads;
4. Weekly loads;
5. Monthly loads;
6. Annual periods;
7. Decadal period.

Table 1. Surface gravity waves loading cases

Loading case	Duration	$H_{1/3}$, m	T_{avg}, s	N	n
Active phase of local storms	3 hours	6.89	9.3	1162	3.5
Standard storms	7 hours	6.00	9.057	2783	3.891
Daily	1 day	3.62	6.522	13 248	4.0
Weekly	1 week	3.19	6.561	92 182	4.418
Monthly	1 month	2.58	6.043	428 927	4.892
Annual	1 year	1.45	4.836	6 521 092	5.327
Decadal	1 decade	0.84	3.863	81 636 035	5.731

Simulation of wave loads is a key point of the analysis. To describe statistical characteristics of surface gravity waves the well-known JONSWAP spectrum model [Hasselman et al., 1973] was employed in the following form (see Fig. 5):

$$S_\eta(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} \exp\left(-\frac{5}{4}\left(\frac{f_m}{f}\right)^4\right) \gamma^{\exp\left(-\frac{(f-f_m)^2}{2\sigma^2 f_m^2}\right)}, \quad (3)$$

where $\gamma = 3.3$, U_w – wind speed at 10 meters above the sea level,

$$\alpha = 0.076 x_m^{-0.22}, \quad (4)$$

$$x_m = gx/U_w^2, \tag{5}$$

$$\sigma = \begin{cases} 0.07 \text{ for } f \le f_m \\ 0.09 \text{ for } f > f_m \end{cases}, \tag{6}$$

x – fetch (m), g – gravity ($м^2/c$), and peak wave frequency is

$$f_m = g/U_w x_m^{0.33}. \tag{7}$$

The peak wave period has been parameterized with the wind-free invariant (1) [Zakharov et al., 2015] as well:

$$T_m \approx 4.4655 H_s^{0.4} x^{0.1}/g^{0.5}. \tag{8}$$

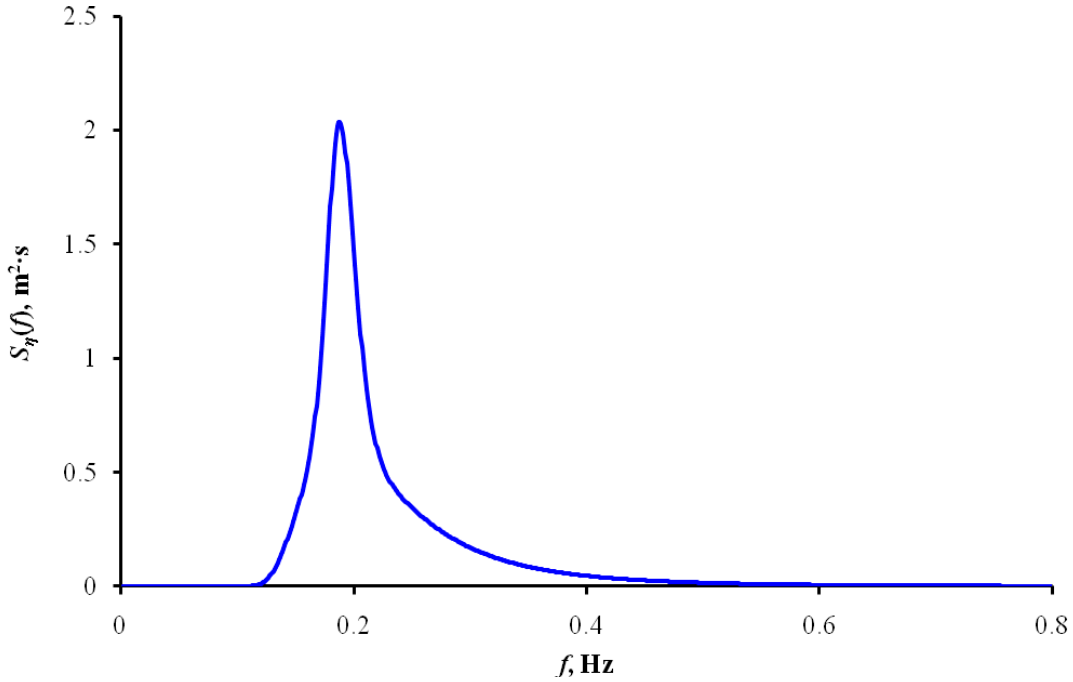

Fig. 5. Spectral density of sea surface elevation for monthly loading case

Transformation from wave spectrum (3) to the horizontal force spectrum (Borgman, 1967) gives (see, for instance, Fig. 6):

$$S_{F_x}(f, z) = \frac{8}{\pi} K_d^2 \sigma_U^2 S_U(f, z) + K_i^2 S_a(f, z), \tag{9}$$

where

$$K_d = \frac{1}{2}\rho C_D D, \tag{10}$$

$$K_i = \rho C_M A, \tag{11}$$

$$\sigma_U^2 = \int_0^\infty S_U(f, z)\,df, \tag{12}$$

$$S_U(f, z) = (2\pi f)^2 \frac{\cosh^2(k(h+z))}{\sinh^2(kh)} S_\eta(f), \tag{13}$$

$$S_a(f, z) = (2\pi f)^4 \frac{\cosh^2(k(h+z))}{\sinh^2(kh)} S_\eta(f). \tag{14}$$

Here D – the buoy diameter (m); A – the buoy cross-section area (m^2); ρ – fluid density ($\mathrm{kg/m^3}$); C_D – drag coefficient; $C_M = C_m + 1$, where C_m – added mass coefficient; $S_U(f, z)$ – power spectral density of the fluid velocity horizontal component; $S_a(f, z)$ – power spectral density of the fluid acceleration horizontal component; h – depth of the sea (m); z – vertical coordinate (m) measured from the sea level with positive axis directed upward; k – wave number (m^{-1}). For a submerged cylindrical body $C_D = 1.2$, $C_M = 2.0$. Dispersion relation for gravity waves at finite depth has been used

$$(2\pi f)^2 = gk \tanh(kh), \tag{15}$$

to get wave number k for a given wave frequency f.

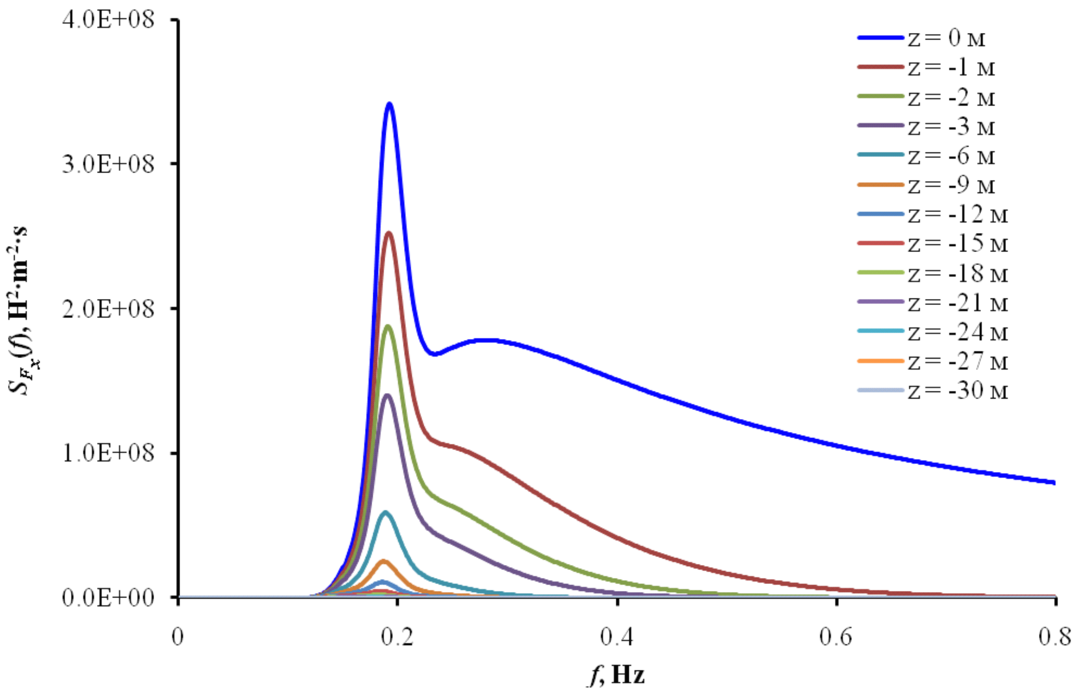

Fig. 6. Spectral density of horizontal component of wave induced force for monthly loading case

Spectral density defined by Eq. (9) was implemented into SIMULIA Abaqus software to perform random response analysis (viscous damping coefficient is set to $\varsigma = 0.025$). Buoy's response in terms of spectral densities and mean root squares of section forces and stresses was obtained. To proceed from statistical characteristics to real ones the following relation for a random quantity x was utilized:

$$\frac{1}{1 - \int\limits_{-n\sigma}^{n\sigma} \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x - x_{mean}}{\sigma}\right)^2\right) dx} > N, \tag{16}$$

where σ – root mean square of a random quantity x, x_{mean} – expectation of a random quantity x, N – number of waves cycles. The denominator of Eq. (16) corresponds to probability P of a random quantity x to be within the range $[-n\sigma,\ n\sigma]$. Hence, root mean squares of section stresses obtained within the random response analysis should be multiplied by n, that corresponds to a particular loading case (see Table 1) with fixed intensity H_s, duration t, mean wave period T_{avg}, and number of wave cycles N to obtain the level of stresses not to be exceeded for a particular loading case.

Buoy's numerical model itself is shown in Fig. 7 (point masses are shown with green squares). The results of buoy quasi-static and random response analysis are given in Table 2.

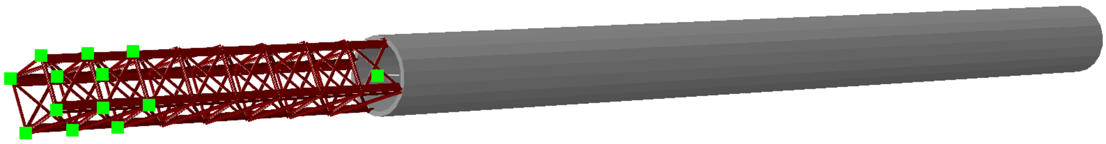

Fig. 7. Buoy's numerical model (point masses are shown with green squares)

Table 2. Extreme stresses in the concrete body of buoy and concrete resistance reduction coefficients for different loading cases

	3 hours	7 hours	1 day	1 week	1 month	1 year	1 decade
$\sigma_{bp}+\lvert\sigma_{b,\min}\rvert$	–	24.638	22.054	21.926	21.270	19.313	18.374
$\sigma_{bp(2)}-\sigma_{b,\max}$	–	2.553	5.137	5.265	5.921	7.878	8.817
$\dfrac{\sigma_{bp(2)}-\sigma_{b,\max}}{\sigma_{bp}+\lvert\sigma_{b,\min}\rvert}$	–	0.1036	0.2329	0.2402	0.2784	0.4079	0.4798
$\prod_i \gamma_{bi}$	–	0.8364	0.8557	0.7492	0.6742	0.7065	0.7036

Here σ_{bp} – concrete pre-stress level, $\lvert\sigma_{b,\min}\rvert$ – absolute value of compressive stress due to external loading, $\sigma_{bp(2)}$ – concrete pre-stress level after all losses, $\sigma_{b,\max}$ –value of tensile stress due to external loading, γ_{bi} – concrete resistance reduction coefficients.

3.2. Fatigue analysis and structure health criteria

The results presented in Table 2 show that the worst loading case corresponds to monthly wave regime as specified by Table 1. Envelope of power spectral densities of stresses in the buoy's concrete body is shown in Fig. 8.

Due to high magnitudes of wave field and relatively low concrete resistance reduction coefficients the submerged part of the buoy is found to be made of concrete with at least C80 grade according to Russian standards and codes to satisfy the following strength and durability requirements:

$$\sigma_{bp(2)}-\sigma_{b,\max}>0\,, \tag{17}$$

$$\sigma_{bp} + \left|\sigma_{b,\min}\right| \le R_b \prod_i \gamma_{bi}\,, \tag{18}$$

where R_b – concrete compression resistance.

Steel mast designed as a space truss made of L-shape profiles should be of S345 grade steel according to Russian standards and codes and the following strength and durability condition:

$$\frac{\max\left(\left|\sigma_{\max}\right|,\ \left|\sigma_{\min}\right|\right)}{\alpha R_v \gamma_v} \le 1 \tag{19}$$

where R_v – fatigue strength, $\alpha \equiv \alpha(N)$, $\gamma_v \equiv \gamma_v\left(\sigma_{\max}/\sigma_{\min}\right)$.

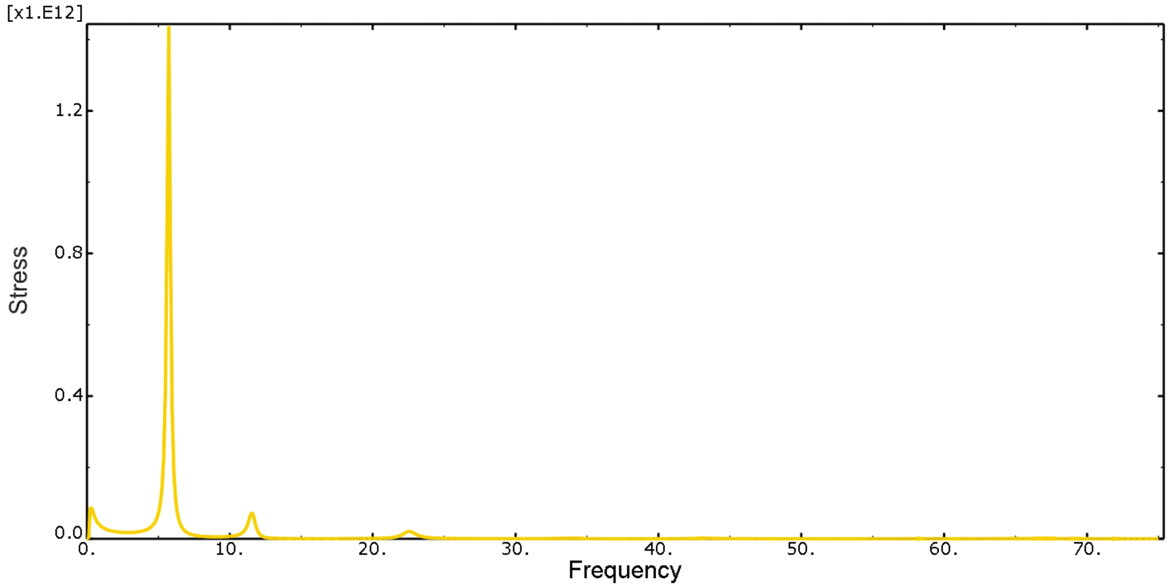

Fig. 8. Envelope of spectral densities $S_{\sigma_{waves}}(f)$ of stresses in buoy's concrete body for monthly loading case

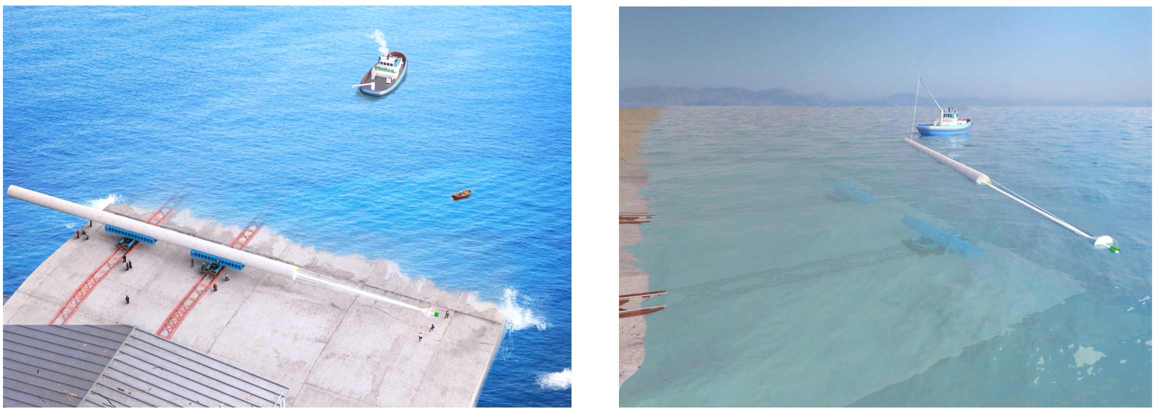

Fig.9. Scheme of the buoy assembling and deployment

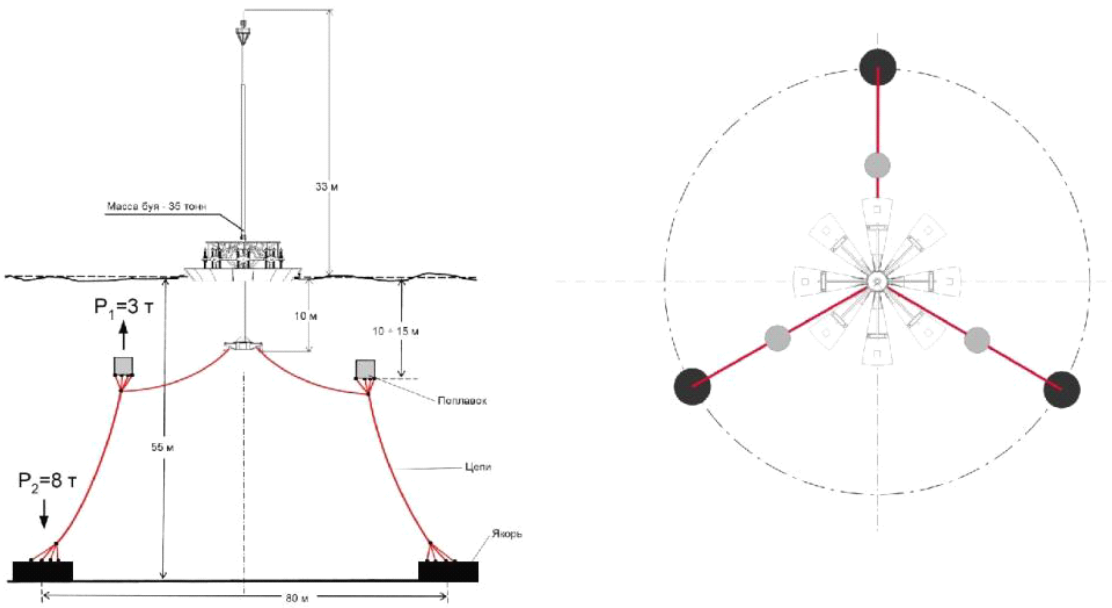

Fig.10. The anchor system of the concrete spar buoy

4. SUMMARY

The key points of this work are summarized below:
1. Feasibility of the stabilized concrete spar buoy for monitoring nearshore zone is substantiated. Key parameters of the buoy (e.g. size, weight etc.) and technological solutions (sectioning, on-site assembling, deployment) have been proposed based on existing codes and regulations as well as taking into account previous experience of field experiments;
2. Recommendations for materials, technologies of manufacturing and methods of the buoy deployment are given on the basis of the strength and fatigue analysis. All the recommendations ensure the buoy lifetime not less than 10 years;
3. Perspectives of the project as a low-cost solutions for nearshore studies and commercial exploitation are discussed. Technical documentation for manufacturing of the buoy concrete body is prepared as a basis for commercialization of the project.

This paper is just a preliminary report on the work done. Many important questions of have not been discussed here. List some of these questions.

Buoy assembling. The propose project is seen as low cost solution that can be realized with minimal financial and technical support in remote places. The buoy is constructed of 3 meter height sections fabricated in workshop conditions and transported on-site by customary trucks.
Buoy deployment. The empty buoy (dry weight 120 tonnes) can be towed by available relatively small vessels. The scheme of the deployment is presented in Fig.9.
Anchor system. In Fig.10 a scheme of anchor system is shown. Three dead anchors on the bottom are made of concrete and connected to three floating concrete sections that damp the spar buoy motions. The P.P.Shirshov Institute has an experience of using such system.

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