doi: 10.18720/MCE.75.5

Reliability of scour protection design near the platform "Prirazlomnaja"

Надежность конструкции защиты от размывов дна вблизи платформы «Приразломная»

V.I. Klimovich,
"B.E. Vedeneev VNIIG", JSC, Saint Petersburg, Russia
K.V. Pariev,
OJSC "Gazprom neft shelf", Saint-Petersburg, Russia

Д-р физ.-мат. наук, гл. науч. сотрудник В.И. Климович,
АО "ВНИИГ им. Б.Е. Веденеева", г. Санкт-Петербург, Россия
начальник отдела К.В. Парьев,
ООО "Газпром нефть шельф", г. Санкт-Петербург, Россия

Key words: design storm; waves; wave spectrum; significant height of wave; peak period of spectrum; erosion; scour protection; rock fill grading; safety criteria

Ключевые слова: расчетный шторм; волны; спектр волнения; значительная высота волн; период пика спектра; размыв; защита от размыва; гранулометрический состав каменной наброски; критерии безопасности

Abstract. Results of experimental researches of scour protection for marine ice-resistant platform (MIRP) "Prirazlomnaja" at impact of irregular waves together with a current are presented and analyzed in the article. Experimental researches were executed taking into account maintenance of the basic similarity criterions. In particular, difference of density of sea water in natural conditions and density of fresh water in modelling conditions was taking into account at physical modelling. The various directions of irregular waves relatively MIRP and various combinations of simultaneous impact of waves and currents were considered at carrying out of experimental researches. On the basis of the natural data and the results of experimental researches safety criteria for scour protection of MIRP "Prirazlomnaja" containing 4 diagnostic parameters and their critical levels (warning and ultimate) were proposed.

Аннотация. В статье приводятся и анализируются результаты экспериментальных исследований защиты от размывов дна для морской ледостойкой платформы (МЛСП) «Приразломная» при воздействии расчетного нерегулярного волнения совместно с течением. Экспериментальные исследования проводились с учетом соблюдения основных критериев подобия. В частности, при физическом моделировании учитывалось отличие плотности морской воды в натурных условиях и пресной воды в модельных условиях. При проведении экспериментальных исследований задавалось различное направление нерегулярного волнения относительно МЛСП и рассматривались различные сочетания одновременного воздействия волн и течений. На основе натурных данных и результатов экспериментальных исследований предложены критерии безопасности для защиты от размывов дна вблизи МЛСП «Приразломная», содержащие 4 диагностических показателя и их критические уровни (предупредительный и предельный).

Introduction

MIRP "Prirazlomnaja" is located in the Pechora Sea. It was moved on the place in 2011 and it was placed in operation in 2013. The first lot of oil from MIRP "Prirazlomnaja" has been shipped in 2014. MIRP "Prirazlomnaja" is the first in the world platform for oil recovery behind polar circle. Scour protection of the bottom for MIRP "Prirazlomnaja", which was realised as two-layer rockfill, had width of the protection layer on the top of 25 m. Experimental researches and designing of scour protection for MIRP "Prirazlomnaja" were made at the usage of regular waves [1].

The considerable number of publications is devoted to researches of scour protection nearby marine hydraulic structures, for example, [2–17]. In the mentioned publications possible variants of scour protection [8, 9], questions of physical and mathematical modelling of rockfill scour protection stability [2–5, 11, 12, 16, 17], features of the hydrodynamic impacts leading to initiation of scour [2–6, 16] are discussed; results of experimental researches are resulted and summarized in [2–4, 7, 8, 13–16]. At the

Климович В.И., Парьев К.В. Надежность конструкции защиты от размывов дна вблизи платформы «Приразломная» // Инженерно-строительный журнал. 2017. № 7(75). С. 52–65.

same time it is necessary to notice that experimental researches are necessarily executed by designing of scour protection nearby the bases of marine platforms of gravitational type. On the basis of these experimental researches the final design of scour protection is fulfilled.

Carrying out of experimental researches for the realized design of scour protection for MIRP "Prirazlomnaja" with width of protective layer on top of 25 m had the purpose to receive an additional substantiation of reliability of scour protection design at hydrodynamic impact from waves (irregular) and currents. Also these experimental researches had to detect necessity of strengthening of scour protection for MIRP "Prirazlomnaja".

Development of safety criteria for scour protection of MIRP "Prirazlomnaja" was defined by necessity of reliable operation and timeliness of acceptance of technical decisions for a non-admission of extreme and abnormal events.

Initial data

Initial data for carrying out of experimental researches of scour protection are presented below. In location of MIRP "Prirazlomnaja" water depth at the mean sea level is 19.4 m, the maximum elevation of sea level at storm surge and tide phenomena repeatability of 1 times in 100 years is 2.2 m. Wave characteristic at a storm repeatability of 1 times in 100 years: the considerable wave height (h_S) - h_S =5.9 m; the peak period of a wave spectrum (T_p) - T_p =15.7 s; wave spectrum is TMA spectrum with spectrum parameter γ = 2.5. Extreme current velocity repeatability of 1 times in 100 years is 1.2 m/s.

Average salinity of water in the location of MIRP "Prirazlomnaja" is 30 ‰, i.e. average density of sea water ρ_w =1030 kg/m^3.

The top soil layer of a sea-bottom (3-5m in depth) in the location of MIRP "Prirazlomnaja" consists basically of sand and sandy loam. Particles with the sizes 0.05–0.25 mm are prevail in grading of the top soil layer.

The design of scour protection for MIRP "Prirazlomnaja" is presented on fig. 1.2. The top protective layer is executed from a stone in the size 0.3-0.4 m. The bottom filter layer is executed from gravel in the size 20–70 mm. Dimensions in plain view of the MIRP "Prirazlomnaja" base are 126 x 126 m.

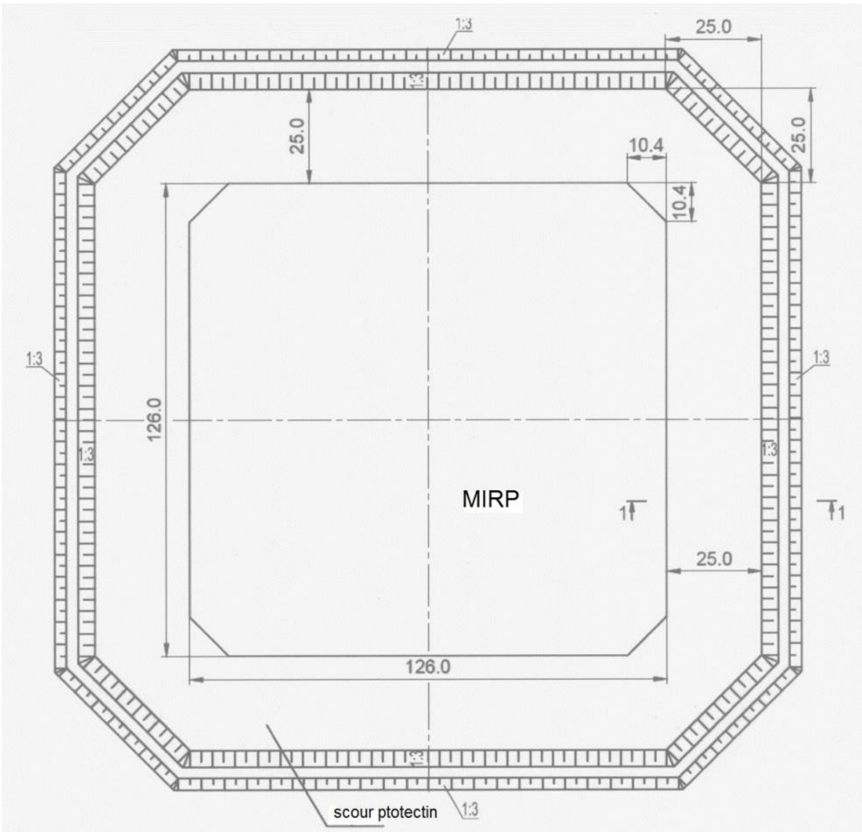

Figure 1. Plan view of scour protection for MIRP "Prirazlomnaja" (the natural sizes)

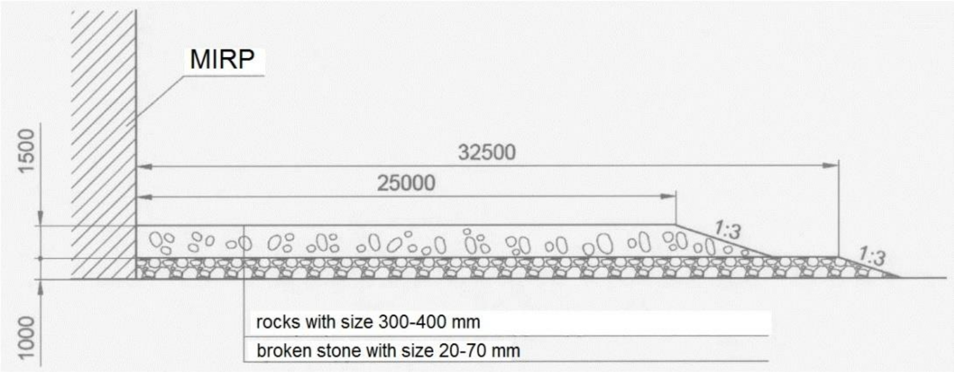

Figure 2. Cross-section of scour protection for MIRP "Prirazlomnaja" (the natural sizes)

Experimental researches

At carrying out of experimental researches the model of base of gravity type (BGT) of MIRP "Prirazlomnaja" was reproduced as geometrically similar to natural BGT. The general view of wave pool, in which researches were conducted, is shown on Figure 3. Below of foreground Figure 3 wave absorber is visible, on the far end of wave pool wavemaker of piston type is located and the hole for water delivery and creation of currents is visible, model BGT and scour protection is located in a zone of wave pool with a scouring material (a thickness of scouring material layer is 30 cm).

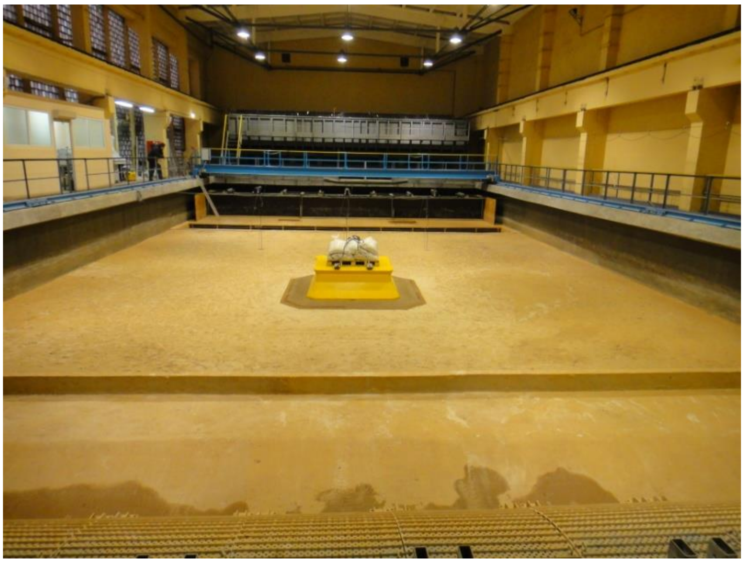

Figure 3. General view of wave basin with BGT of MIRP "Prirazlomnaja"

The basic modern requirements for experimental researches of wave impact on hydraulic facilities (HF) and their separate elements are resulted in [16]. In particular, the model scale according to [16] should satisfy a condition that the considerable height of waves on model was more than 0.05 m (as a rule, linear scale of model is greater 1:60). Herewith it is especially noticed that for the mostfull modelling of wave natural conditions it is required to reproduce irregular waves with specified spectrum. Also the special requirement is imposed to elimination of the reflected waves in modelling conditions – it is supposed reflexion no more 5 % of waves.

In the present researchers the linear scale of model has been chosen 1:60 (λ = 60). Firstly, the choice of this model scale was caused by requirements [16]. Secondly, stream constriction at impact of waves and currents in modelling conditions can lead to essential defect of hydrodynamic modeling results (the width of a modelling basin has the fixed size and for enough big sizes of model it can lead to flow defect). The width of a modelling wave basin of JSC “The B.E.Vedeneev VNIIG” was 15 m, the characteristic linear planned size of model **(**B**)** at scale 1:60 was B = 2.1 m (or 3 m if waves are directed at an angle 45^0 to a plane of one side of the platform). Thus, already at model scale 1:60 in the conditions of VNIIG wave basin the obstruction factor (the ratio of effective cross-section and full section of a modelling basin) was 0.86 (or 0.8).

At modelling on the basis of geometrical similarity, similarity of Froude numbers **(**Fr**)**

$$Fr = V/(gd)^{0.5}$$

and time scale as $\lambda^{0.5}$, scales of physical characteristics can be defined according to table 1 (V – velocity, g – acceleration of free falling, d – depth)

Table 1. Scales of model characteristics

Name	Scale	Scale for *l*=60
length	λ	60
square	λ^2	2600
volume	λ^3	216000
time	$\lambda^{0.5}$	7.75
velocity	$\lambda^{0.5}$	7.75
mass*)	λ^3	216000

*) concerning a choice of modelling stone weight of a protective layer see the following explanation.

The difference in density of water for modelling and natural conditions affects on the forces which impact at stones of a protective layer. Therefore for correct modelling it is necessary to estimate quantity of this effect and to choose correct scale of modelling stone weight of a protective layer (in modelling conditions use, as a rule, fresh water). In [16] for the account of the above described effect it is offered to have similarity on stability parameter (N_s)

$$N_S = h_S \,/\, (\Delta D_{50}), \qquad \Delta = (\rho_r - \rho_w)\,/\,\rho_w$$

Here D_{50} – average diameter of stone, ρ_r – stone density, ρ_w – water density.

Hereby, for correct modelling of hydrodynamic impact at the stones of protective layer with account of equality of stability parameter in natural and modelling conditions it is necessary to change size of stones of protective layer (D_{50}) as follows (the index “m” concerns to model, an index “p” – to nature)

$$\frac{D_{50,m}}{D_{50,p}} = \frac{1}{\lambda}\frac{\Delta_p}{\Delta_m}$$

Assuming that stone density in nature and in model conditions are equal $\rho_{r,p}=\rho_{r,m}$=2650 kg/m^3, we receive that the scale of protective layer stone size should be equal $\lambda_{r,\,diam}$= 63.

Let us notice that taking into account the chosen scale of model λ =60 it is impossible to make correct modelling of the material composing a bottom in location MIRP "Prirazlomnaja" as the size of modelling bottom material should be less 0.01 mm. Therefore sizes of scour of a bottom near scour protection for model conditions it is necessary to consider as estimating, however locations of zones with possible maximum scouring in depth of unprotected bottom can be detected. The sea-bottom in VNIIG wave basin was modelled by sand with size D_{50}=0.16 mm.

Reynolds's number $Re=V\cdot d/\nu$ (also Reynolds's numbers $Re=V\cdot h/\nu$, $Re=V\cdot B/\nu$, ν – kinematic coefficient of viscosity) for modelling conditions exceeded 0.5·10^5 that corresponds to automodelling area. Reynolds's number $Re_*=V_*\cdot D_{50}/\nu$ ($V_* = \sqrt{\tau/\rho}$ – dynamic velocity, τ – shear stress on bottom, defined according [16]) for modelling conditions exceeded 3.0·10^2 that corresponds to area of independence of critical value of Shields parameter from Re_*.

Experimental researches of scour protection for MIRP "Prirazlomnaja" were executed as sequence of tests for each of two wave directions to plane side of platform (45 ^{o} and 90 ^{o}) at design scenario (waves for a storm with repeatability 1 times in 100 years and a current with repeatability 1 times in 100 years) according to the data presented in Table 2.

Carrying out of researches in the presence of a co-ordinated current, in the absence of a current and at the account of wave transformation on opposite current allows to envelope all range of possible hydrodynamic impacts on scour protection at the design storm. Necessity of execution of the test No. 3 explains that for currents and waves with opposite directions the height of waves for conditions of MIRP "Prirazlomnaja" increases in 1.1 times (see [18]). The sequence of experiments has been chosen taking into account increase of wave impact (in the presence of a co-ordinated current the wave height was minimum, and for wave transformation on opposite current the wave height was maximum).

Table 2. Parameters of the executed tests for wave directions with angle 90º and 45º to a plane of side of MIRP "Prirazlomnaja" base

№№	Wave nature/model (*l*=60)		Current nature/model	Duration nature/model		Note
	h_s, m	T_p, s	V_{av}, m/s	test duration	total time of impact	
1a	5.9/0.098	15.7/2.03	1.2/0.155	3h/23.25min	3h/23.25min	waves+current with repeatability 1 times in 100 years co-ordinated in a direction
1b	5.9/0.098	15.7/2.03	1.2/0.155	3h/23.25min	6h/46.5min	waves+current with repeatability 1 times in 100 years co-ordinated in a direction
1c	6.5/0.108	15.7/2.03	1.2/0.155	6h/46.5min	12h/93min	waves+current with repeatability 1 times in 100 years co-ordinated in a direction
2	5.9/0.098	15.7/2.03	0	6h/46.5min	18h/139.5min	Waves (without current) with repeatability 1 times in 100 years
3	6.5/0.108	15.7/2.03	-	6h/46.5 min	24h/186.0min	Correspond to wave parameter for opposite current

Separate experiments were executed during time which correspond to duration of peak of design storm 3–6 hours of natural time (it was also useful for estimation of dynamics of bottom and scour protection deformations).

The protective layer stones of MIRP "Prirazlomnaja" were modelled by means of gravel, which grain-size distribution is presented on Figure 4. We will notice that grain-size distribution has been received by means of gravel sifting through a set gauging sieves.

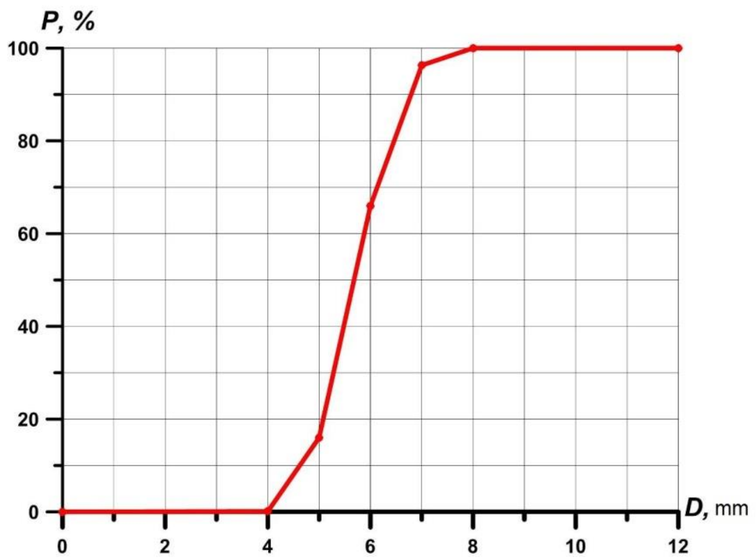

Figure 4. Model grain-size distribution of protective layer stones

Average diameter of a modelling material was D_{50} = 5.65 mm (Fig. 4) that will be co-ordinated good enough with required on criteria of similarity value 350/63 = 5.56 mm. Also it is necessary to notice that in a range *P* from 10 % to 90 % there was a material with size from 4.7 mm to 6.8 mm (that in recalculation for the natural sizes coincides well with a required range 300–400 mm).

The model filter layer was reproduced by means of sand with size 0.4–1.1 mm that will be co-ordinated good enough with required on criteria of similarity nature value 20–70 mm. The model grain-size distribution of the filter layer material is shown on Figure 5.

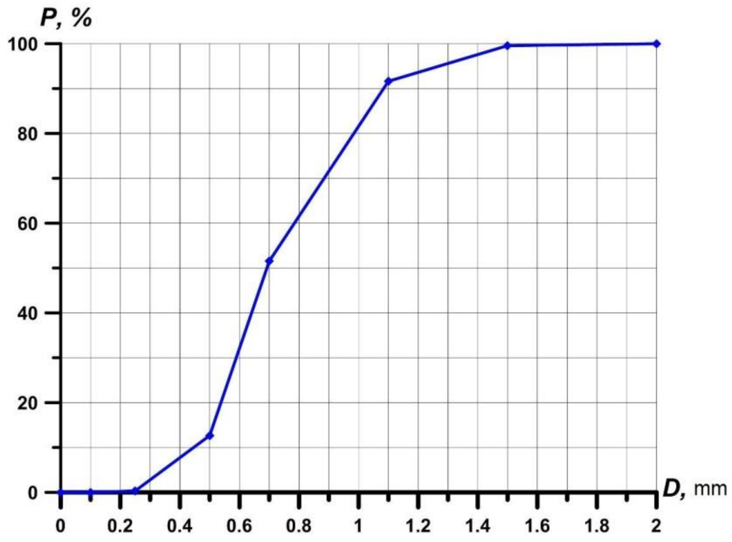

Figure 5. Model grain-size distribution of filter layer material

At calibration of current characteristics it was taken into consideration that the theoretical profile of velocity should change under the logarithmic law [19]:

$$U(z) = V_{cp}\frac{8.5 + 2.5ln(z/k)}{6.5 + 2.5ln(d/k)}$$

Here *k* – roughness parameter (*k* = $2.5D_{50}$ [4]), *z* – vertical coordinate.

Results of comparison of the measured and theoretical distributions of velocity on depth for current modelling with repeatability 1 times in 100 years are shown on Figure 6, Velocity measurements were made by means of the velocity gauge MiniWater20Micro.

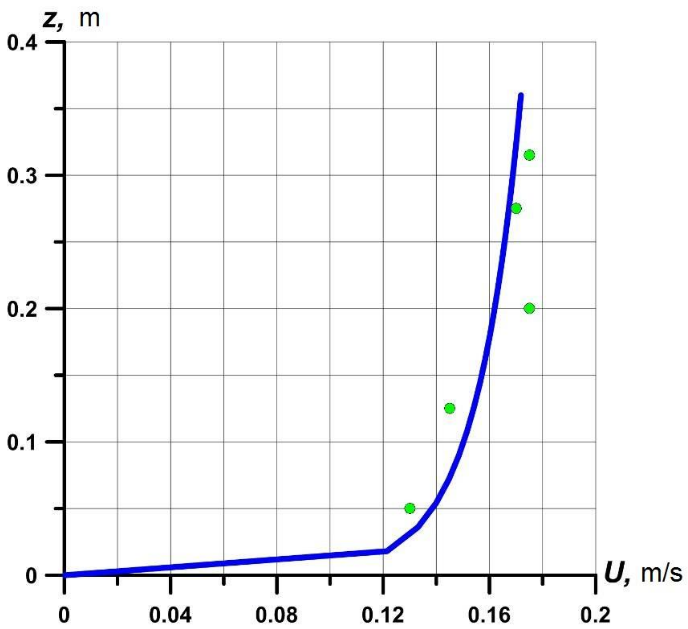

Figure 6. Distribution of current velocity on depth (repeatability – 1 times in 100 years) for model conditions (——— – theoretical profile of velocity, ● – measured value of velocity)

Vertical distribution of velocity for chosen location of model MIRP "Prirazlomnaja" will be co-ordinated well enough with theoretical profile for the steady turbulent flows (Fig.6).

At calibration of wave conditions the possible location of model MIRP "Prirazlomnaja" was defined so to receive demanded wave characteristics in this place. As example, comparison of the required and measured wave spectra for tests 1,2 (table 2) is shown on Figure 7.

Klimovich V.I., Pariev K.V. Design reliability for scour protection of the bottom near the platform "Prirazlomnaja". *Magazine of Civil Engineering*. 2017. No. 7. Pp. 52–65. doi: 10.18720/MCE.75.5.

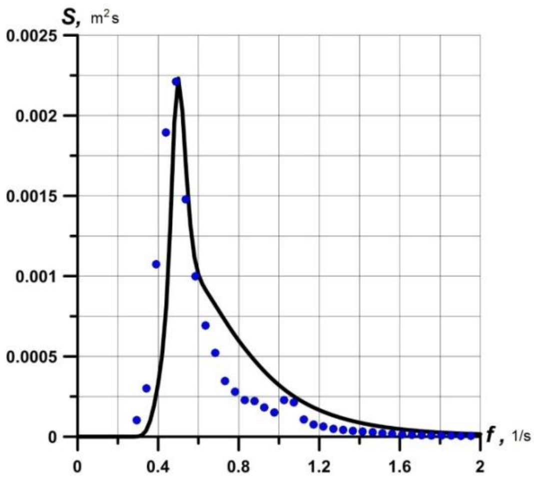

Figure 7. Wave spectrum for conditions of tests 1,2 with repeatability 1 times in 100 years (——— – required distribution, ● – measured value)

Results and Discussion

The first series of experiments was executed for wave direction with angle 90° to a plane side of BGT. Certain moments and results of the executed experimental researches are shown on Figures 8–12. Measurements of scour protection and bottom levels around model BGT were made by means of Trimble M3 total station (the error of measurements did not exceed 1 mm). Data on dynamics of scour protection and bottom levels are presented on Figures 13–15.

Figure 8.View on BGT model and scour protection before the beginning of experimental researches for wave direction with angle 90° to a plane side of BGT

Figure 9. Interaction of waves with BGT during execution of researches for wave direction with angle 90° to a plane side of BGT "Prirazlomnaja" (view from windward side)

Figure 10. View on BGT model and scour protection (from leeward side) after after execution of tests 1a, 1b, 1c, 2, 3 for wave direction with angle 90^o to a plane side of BGT "Prirazlomnaja"

Figure 11. View on BGT model and scour protection (from windward side) after after execution of tests 1a, 1b, 1c, 2, 3 for wave direction with angle 90^o to a plane side of BGT "Prirazlomnaja"

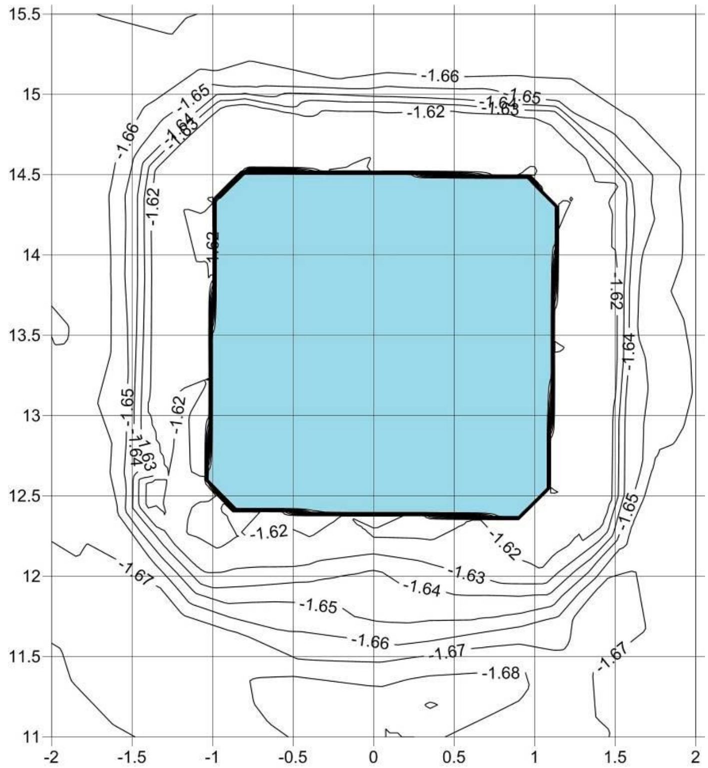

Figure 12. Plan of scour protection levels after execution of tests 1a, 1b, 1c, 2, 3 for wave direction with angle 90^o to a plane side of BGT "Prirazlomnaja" (level – 1.62 m corresponds to the top level of scour protection before researches)

The geometry of the central section of windward scour protection face after execution of corresponding tests (Table 2) is shown on Figure 13.

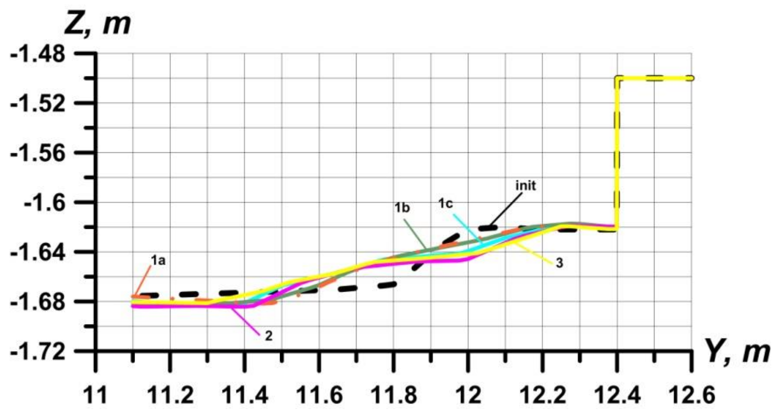

Figure 13. Geometry of the central section of windward scour protection face after execution of tests 1a, 1b, 1c, 2, 3 for wave direction with angle 90º to a plane side of BGT "Prirazlomnaja" (— — — – initial geometry).

Let us notice that the leeward face geometry, and also lateral faces of scour protection after execution of 5 tests has not changed practically. On Figures 14, 15, for example, the geometries of the central sections of left side face and leeward face of scour protection are shown after execution of tests 1a, 1b, 1c, 2, 3.

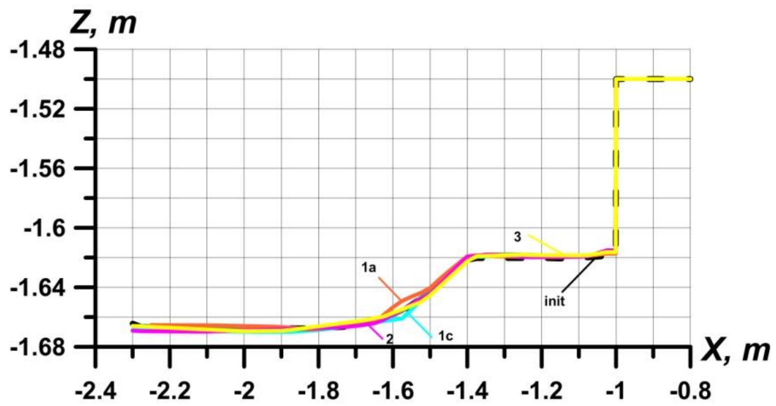

Figure 14. Geometry of the central section of left side scour protection face after execution of tests 1a, 1b, 1c, 2, 3 for wave direction with angle 90º to a plane side of BGT "Prirazlomnaja" (— — — – initial geometry)

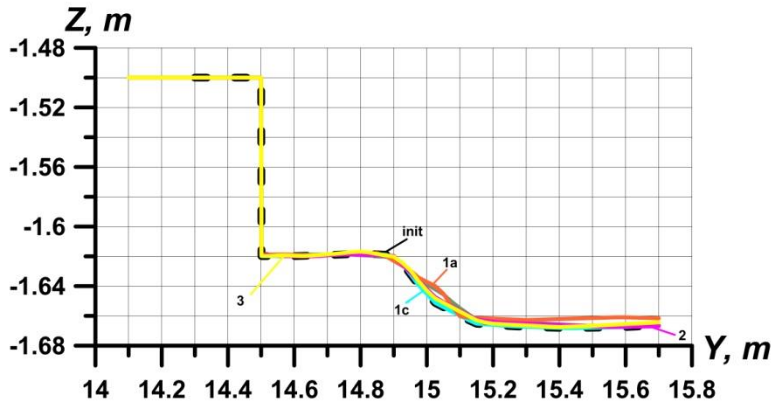

Figure 15. Geometry of the central section of leeward scour protection face after execution of tests 1a, 1b, 1c, 2, 3 for wave direction with angle 90º to a plane side of BGT "Prirazlomnaja" (— — — - initial geometry)

Small deformations of a protective layer were observed near to angular points of interface of windward face with the cutaway corners of BGT. The maximum vertical deformation (scour) of protective layer in these local zones near to angular points after execution of all 5 tests did not exceed 1 sm and was not critical.

Let us notice that after 24 hours of impact of a storm with repeatability of 1 times in 100 years scour protection with width of a protective layer 25 m (on top) has kept the function of protection of the foundation from scour for a case of wave direction with angle 90º to a plane side of BGT. As follows from Figures 13–15, deformations of scour protection induced of waves for a design storm in any combination with a current are stabilized after ~18–24 hours. Herewith adjacent part of protective layer on distance 10–12 m (the natural sizes) from BGT surface was not deformed except vicinity of angular points of BGT where vertical size of scour can reach 0.6 m (in natural conditions).

The second series of experiments was executed for wave direction with angle 45º to a plane side of BGT. Certain moments and results of the executed experimental researches are shown on Figures 16, 17.

Figure 16. Interaction of waves with BGT during execution of researches for wave direction with angle 45º to a plane side of BGT "Prirazlomnaja" (view from windward side)

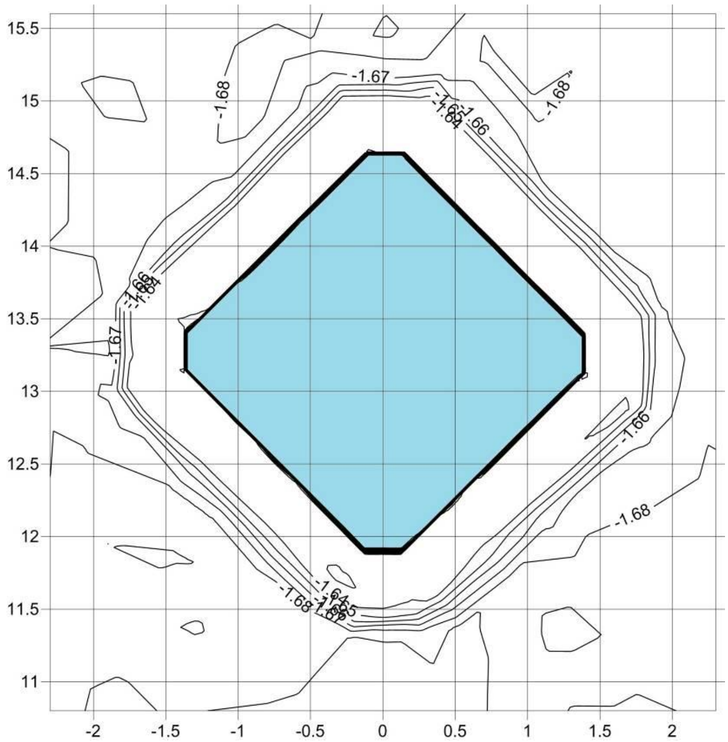

Figure 17. Plan of scour protection levels after execution of tests 1a, 1b, 1c, 2, 3 for wave direction with angle 45º to a plane side of BGT "Prirazlomnaja" (level – 1.64 m corresponds to the top level of scour protection before researches)

Let us notice that after 24 hours of impact of a storm with repeatability of 1 times in 100 years scour protection with width of a protective layer 25 m (on top) has kept the function of protection of the foundation from scour for a case of wave direction with angle 45° to a plane side of BGT. Scour protection surface practically was not deformed except vicinity of angular points of BGT where vertical size of scour can reach 0.6 m (in natural conditions).

As it was noted in [2], at present time there are no empirical relations allowing reliably to predict size of bottom scours for marine hydraulic structures of the big sizes and any form. Even for cylindrical piles with big diameters for values of Keulegan-Carpenter numbers (*KC*) *KC* <1 prognosis of a bottom scours is not possible [2]. In experimental researches of scour protection of the bottom for MIRP "Prirazlomnaja" the Keulegan-Carpenter number was equal $KC \approx 0{,}2$.

The obtained experimental results about scours of unprotected bottom near to rockfill for MIRP "Prirazlomnaja" have been co-ordinated in whole with the data [1]. Scours of unprotected bottom in the presented experiments were about 1.2–1.8 m, in [1] scours of unprotected bottom (scour protection had width on top of 20 m) were 1.5–2.5 m. The stabilization time of a protective layer deformations under impacts of design waves and currents in the present experimental researches was some more than in [1]. Unfortunately, in [1] it has not been given the concrete data about protective layer deformations, therefore it is not possible to spend comparison of this data at impacts of irregular (in the present experiments) and regular waves (in [1]).

Experimental results on protective layer deformations under design impacts of waves and currents show that the realized scour protection provides reliable protection of a bottom. These results should be considered in development of safety criteria of scour protection for MIRP "Prirazlomnaja".

Safety criteria

In the present domestic and foreign normative literature [2, 16, 20–24] do not contain specific requirements to setting of safety criteria for scour protection near marine stationary platforms. In [16] (chapter 10) it explains by means of the big variety of natural conditions and a variety of platform base designs. The general recommendations for setting of safety criteria assume the presence of the natural data on a situation of scour protection and presence of experimental data on behaviour of scour protection under design impacts. As an example the natural data for one of scour protection cross profile located near to the center of North face of MIRP "Prirazlomnaja" are shown on Figure 18. Comparing the data on the monitoring, which was spent in 2012-2016, and results of experimental researches of scour protection it is possible to notice that character of scour protection deformations at wave impacts in natural and laboratory conditions are coordinated in whole. It is observed flattening of a scour protection slope, the basic deformations (scours) of a protective layer are observed in the central part of the scour protection faces, significant scours in a zone adjoining to BGT on distance of 10–12 m is not observed. Such agreement of the natural and laboratory data, which were received independently, indicates that monitoring and experimental researches were executed at good level.

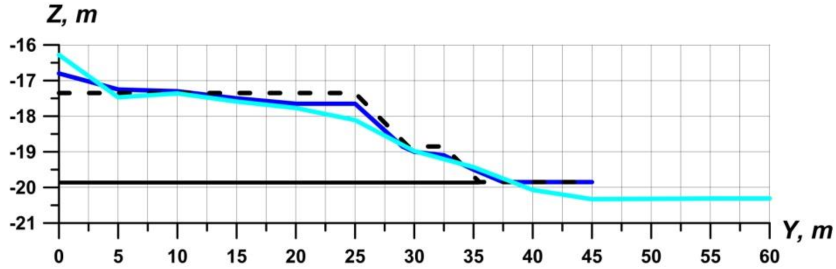

Figure 18. Natural data on the changes of geometry of scour protection section located near to the center of North face of MIRP "Prirazlomnaja" - - - - – a design profile, ——— – a profile after building of scour protection in 2011, ——— – a profile in conditions of 2016).

According to results of experimental researches different parts of scour protection were deformed differently (the central part of scour protection faces can be deformed much more strongly, than that which were located more close to edge, see Figure12). Therefore it is reasonably to divide each of lateral scour protection faces on 4 segments, and also to consider in addition segments of scour protection, adjoining to the cutaway corners of BGT. In total, thus, it will be possible to consider 20 segments of scour protection. Safety criteria will be applied to each segment separately and the total condition of scour protection will be estimated on a segment with the worst condition.

As the diagnostic indicators, characterizing a condition of scour protection of MIRP "Prirazlomnaja", it is proposed to use:

- the area of scour (level lowering) of a protective layer, exceeding the specified critical value from design level, in a zone adjoining to the base of a platform on distance of 12 m (D1);

- depth (in meters) local scour (level lowering) of a protective layer from design level (D2);

- a steepness of scour protection slopes (D3);

- depth of local scours of unprotected bottom near to scour protection on distance 10м from outside of scour protection (D4).

For diagnostic indicator D1 the criterion of condition K1 (warning level) is offered from a requirement that on distance of 12 m from the BGT of MIRP "Prirazlomnaja" the total area where scour exceeds average stone size (D_{50}= 0.35 m), makes more than 50 % from the area of a considered zone for each segment. The criterion of condition K2 (ultimate level) for diagnostic indicator D1 is offered from a requirement that on distance of 12 m from the BGT of MIRP "Prirazlomnaja" the total area where scour exceeds half of protective layer thickness (0.75 m), makes more than 50 % from the area of a considered zone for each segment. We will notice that changes of diagnostic indicator D1 can be connected with protective layer scours as a result of wave impacts and also with subsidence of a protective layer as a result of washing away of filter layer particles.

For diagnostic indicator D2 the criterion of condition K1 (warning level) is offered from a requirement that on distance of 12 m from the BGT of MIRP "Prirazlomnaja" depth of local scours of a protective layer make no more than two average diameters of a stone (0.7 m) for each considered segment. The criterion of condition K2 (ultimate level) for diagnostic indicator D2 is offered from a requirement that on distance of 12 m from the BGT of MIRP "Prirazlomnaja" depth of local scours of a protective layer make no more than three average stone diameters (1.05 m) for each considered segment. We will notice that introduction of diagnostic indicator D2 is connected with possible ice impacts and also with influences on scour protection from falling subjects which can affect on its ability to protect of a sea-bottom near platform from scours.

For diagnostic indicator D3 the criterion of condition K1 (warning level) is offered from a requirement that the steepness of a slope does not exceed the design level (1 to 3) for each considered segment. The criterion of condition K2 (ultimate level) for diagnostic indicator D3 is offered from a requirement that the steepness of a slope does not exceed a natural steepness of a stone slope under water (1 to 1.2) for each considered segment. We will notice that introduction of diagnostic indicator D3 is connected with possible ice influences and also with the possible underwater landslips because of washing away of filter layer particles and particles of a bottom soil.

For diagnostic indicator D4 the criterion of condition K1 (warning level) is offered from a requirement that depth of local scour of unprotected bottom on distance of 10 m from outside of scour protection does not exceed 2.0 m for each considered segment. The criterion of condition K2 (ultimate level) for diagnostic indicator D4 is offered from a requirement that depth of local scour of unprotected bottom on distance of 10 m from outside of scour protection does not exceed 6.0 m for each considered segment. We will notice that introduction of diagnostic indicator D4 is connected with possible scours of unprotected bottom which can lead to transformation of scour protection slopes. Choice of level K1 equal of 2.0 m was made because of scour depth of unprotected bottom did not exceed 2.0 m in experimental researches and in natural observations. Choice of level K2 equal of 6.0 m was made because of such scour depth of unprotected bottom near scour protection for design steepness of slope begins to affect on area located on distance of 12 m from the BGT of MIRP "Prirazlomnaja".

The total condition of scour protection for MIRP "Prirazlomnaja" is offered to estimate according [25]. If diagnostic indicators D1-D4 do not exceed criterion K1 for all 20 segments then total condition of scour protection is estimated as normal. If at least one of diagnostic indicators D1-D4 exceed criterion K1 for any segment and do not exceed criterion K2 total condition of scour protection is estimated as potentially dangerous. If at least one of diagnostic indicators D1-D4 exceed criterion K2 for any segment total condition of scour protection is estimated as abnormal.

At present time according results of natural observations in 2016 the total condition of scour protection for MIRP "Prirazlomnaja" is normal.

Conclusions

1. Experimental researches of scour protection for MIRP "Prirazlomnaja" were executed at design hydrodynamic impact from waves (irregular) and currents. It was shown that at impact of design storm with various combinations to a design current scour protection with width of a protective layer on top 25 m and stone sizes of a protective layer 0.3-0.4 m provides reliable protection of a bottom against scour near BGT at various directions of waves to MIRP "Prirazlomnaja".

2. Safety criteria for scour protection of MIRP "Prirazlomnaja" based on results of experimental researches and natural data on a state of scour protection were proposed.

3. By the results of natural observations in 2016 the technical condition of scour protection for MIRP "Prirazlomnaja" according to the accepted criteria of safety is estimated as normal.

References

1. Devis M.Kh., Mishchenko S.M. Eksperimentalnoye issledovaniye mestnykh razmyvov dna u osnovaniya morskikh gidrotekhnicheskikh sooruzheniy [Experimental study of local erosion of the bottom at the base of marine hydraulic structures]. *Izvestiya VNIIG.* 2000. Vol. 236. Pp. 140–151.
2. Sumer B.M., Fredsoe J. *The Mechanics of Scour in the Marine Environment.* Singapore. Word Scientific. 2002. 536 p.
3. Whitehouse R. *Scour at Marine Structure.* Thomas Telford. London. 1998. 216 p.
4. Hoffmans G., Verheij H. *Scour manual.* Balkema. Netherland. 1997. 224 p.
5. Annandale G. *Scour Technology. Mechanics and Engineering Practice.* Mc Grow-Hill. 2006. 368 p.
6. *EM 1110-2-1100.* The coastal engineering manual. US Army Corps. of Engineers. 2002.
7. May R., Ackers J., Kirby A. *Manual on scour at bridges and other hydraulic structure.* CIRIA. London. 2002. 225 p.
8. Khalfin I.Sh. *Vozdeystviye voln na morskiye neftegazo-promyslovyye sooruzheniya.* M.: Nedra. 1990. 311 c.
9. Belyaev N.D., Lebedev V.V., Nudner I.S., Semenov K.K., Shchemelinin D.I. Selection of protective measures against scouring at the foundations of offshore gravity platforms. *Magazine of Civil Engineering.* 2015. No. 3(55). Pp. 79–88. (rus)
10. Whitehouse R., Harris J., Sutherland J., Rees J. The nature of scour development and scour protection of offshore windfarm foundations // Marine Pollution Bulletin. 2011. Vol. 62. No. 1. Pp. 73–88.
11. Rudolph D., Raaijmakers T.C., Sonneville B. Challenges and recent advances in offshore scour modeling. *12th International Conference The JACK-UP PLATFORM Design, Construction & Operations.* London, UK, 2009.
12. Sumer B.M. Mathematical modeling of scour: A review. *J.of Hydraulis research.* 2007. Vol. 45. No. 6. Pp. 723–735.
13. Sumer B.M., Nielsen A.W. Sinking failure of scour protection at offshore wind turbine foundation. *Proceedings of the ICE-Energy. ICE.* 2013. Vol. 166(4). Pp. 170–188.
14. Vos L.D, De Rouck J., Troch P., Frigaard P. Empirical design of scour protections around monopile foundations: Part 1: Static approach. *Coastal Engineering.* 2011. Vol. 58. No. 6. Pp. 540–553.
15. Vos L.D, De Rouck J., Troch P., Frigaard P. Empirical design of scour protections around monopile foundations: Part 2: Dynamic approach. *Coastal Engineering.* 2012. Vol. 60. Pp. 286–298.
16. *CIRIA, CUR, CETMEF.* The Rock Manual/ The use of rock in hydraulic engineering (2-nd edition). C683, CIRIA, London, 2007. 1267 p.
17. Semenov K.K., Lebedev V.V., Nudner I.S., Geidarov N.A., Ivanov K.S., Zagharov Yu.N., Belyaev N.D., Mishina A.V., Schemelinin L.G. Impacts of waves and currents on the soil near gravity-tipe offshore platform foundation. *Proceedings*

Литература

1. Дэвис М.Х., Мищенко С.М. Экспериментальное исследование местных размывов дна у основания морских гидротехнических сооружений// Известия ВНИИГ. 2000. Т. 236. С. 140–151.
2. Sumer B.M., Fredsoe J. The Mechanics of Scour in the Marine Environment. Singapore. Word Scientific. 2002. 536 p.
3. Whitehouse R. Scour at Marine Structure. Thomas Telford. London. 1998. 216 p.
4. Hoffmans G., Verheij H. Scour manual. Balkema. Netherland. 1997. 224 p.
5. Annandale G. Scour Technology. Mechanics and Engineering Practice. Mc Grow-Hill. 2006. 368 p.
6. EM 1110-2-1100. The coastal engineering manual. US Army Corps. of Engineers. 2002.
7. May R., Ackers J., Kirby A. Manual on scour at bridges and other hydraulic structure. 2002. CIRIA. London. 225 p.
8. Халфин И.Ш. Воздействие волн на морские нефтегазо-промысловые сооружения. М.: Недра. 1990. 311 с.
9. Беляев Н.Д., Лебедев В.В., Нуднер И.С., Семенов К.К., Щемелинин Д.И. Выбор мероприятий по защите от размыва оснований гравитационных платформ для освоения шельфа // Инженерно строительный журнал. 2015. № 3. С. 79–88.
10. Whitehouse R., Harris J., Sutherland J., Rees J. The nature of scour development and scour protection of offshore windfarm foundations // Marine Pollution Bulletin. 2011. Vol. 62. № 1. Pp. 73–88.
11. Rudolph D., Raaijmakers T.C., Sonneville B. Challenges and recent advances in offshore scour modeling // 12th International Conference The JACK-UP PLATFORM Design, Construction & Operations. London, UK, 2009.
12. Sumer B.M. Mathematical modeling of scour: A review // J.of Hydraulis research. 2007. Vol. 45. № 6. Pp. 723–735.
13. Sumer B.M., Nielsen A.W. Sinking failure of scour protection at offshore wind turbine foundation // Proceedings of the ICE-Energy. ICE. 2013. Vol. 166(4). Pp. 170–188.
14. Vos L.D, De Rouck J., Troch P., Frigaard P. Empirical design of scour protections around monopile foundations: Part 1: Static approach // Coastal Engineering, 2011. Vol. 58. № 6. Pp. 540–553.
15. Vos L.D, De Rouck J., Troch P., Frigaard P. Empirical design of scour protections around monopile foundations: Part 2: Dynamic approach // Coastal Engineering. 2012. Vol. 60. Pp. 286–298.
16. CIRIA, CUR, CETMEF. The Rock Manual/ The use of rock in hydraulic engineering (2-nd edition). C683, CIRIA, London, 2007. 1267 p.
17. Semenov K.K., Lebedev V.V., Nudner I.S., Geidarov N.A., Ivanov K.S., Zagharov Yu.N., Belyaev N.D., Mishina A.V., Schemelinin L.G. Impacts of waves and currents on the soil near gravity-tipe offshore platform foundation // Proceedings of the 25th International Offshore and Polar

of the 25th International Offshore and Polar Engineering Conference. USA. 2015. Vol. 2. Pp. 807–814.
18. Gurgenidze A.T., Trapeznikov YU.A., Rumyantseva S.A. et al. *Teoreticheskiye osnovy i metody rascheta vetrovogo volneniya* [Theoretical bases and methods for calculating wind waves]. Leningrad: Gidrometeoizdat, 1988. 263 p.
19. Loytsyanskiy L.G. *Mekhanika zhidkosti i gaza. 3-ye Izdaniye* [Mechanics of liquid and gas]. Moscow: Nauka, 1970. 904 p.
20. *ISO 19906:2010.* Petroleum and natural gas industries — Arctic offshore structures. Brussels. 2010. 465 p.
21. *Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms – Working Stress Design.* American Petroleum Institute. 2000.
22. *CAN/CSA-S471-92.* General Requirements, Design Criteria, the Enviroment, and Loads/ Forming Part of the Code for the Design, Construction, and Installation of fixed Offshore Structures.
23. Russian State Standard GOST R 54483-2011. Platformy morskiye dlya neftegazodobychi. Obshchiye trebovaniya [Marine platforms for oil and gas production. General requirements]. Moscow, 2012. 26 p.
24. Russian Set of Rules SP 23.13330.2011. Osnovaniya gidrotekhnicheskikh sooruzheniy [Foundations of hydraulic structures]. Moscow, 2011. 109 p.
25. *RD 153-34.2-21.342-00. Metodika opredelenia kriteriev bezopasnosti gidrotehnicheskih sooruzheniy.* [Guidance document RD 153-34.2-21.342-00. Method for determination of safety criteria of hydraulic structures] Moscow. 2000. 16 p. (rus).

Engineering Conference. USA. 2015. Vol. 2. Pp. 807–814.
18. Гургенидзе А.Т., Трапезников Ю.А., Румянцева С.А. и др. Теоретические основы и методы расчета ветрового волнения. Под ред. Давидана И.Н.. Л.: Гидрометеоиздат, 1988. 263 с.
19. Лойцянский Л.Г. Механика жидкости и газа. 3-е Издание. М.: Наука, 1970. 904 с.
20. ISO 19906:2010. Petroleum and natural gas industries — Arctic offshore structures. Brussels. 2010. 465 p.
21. Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms – Working Stress Design. American Petroleum Institute. 2000.
22. CAN/CSA-S471-92. General Requirements, Design Criteria, the Enviroment, and Loads/ Forming Part of the Code for the Design, Construction, and Installation of fixed Offshore Structures.
23. ГОСТ Р 54483-2011. Платформы морские для нефтегазодобычи. Общие требования. М., 2012. 26 с.
24. СП 23.13330.2011. Основания гидротехнических сооружений. Актуализированная редакция СНиП 2.02.02-85. М., 2011. 109 с.
25. РД 153-34.2-21.342-00. Методика определения критериев безопасности гидротехнических сооружений. М., 2000. 16 с.

Vitaly Klimovich,
+7(812)4939353; klimvita@yandex.ru

Konstantin Pariev,
+7(981)1992403; Parev.KV@gazprom-neft.ru

Виталий Иванович Климович,
+7(812)4939353; эл. почта: klimvita@yandex.ru

Константин Владимирович Парьев,
+7(981)1992403;
эл. почта: Parev.KV@gazprom-neft.ru

Klimovich V.I., Pariev K.V. Design reliability for scour protection of the bottom near the platform "Prirazlomnaja". *Magazine of Civil Engineering*. 2017. No. 7. Pp. 52–65. doi: 10.18720/MCE.75.5.