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Determination of local scours near platforms at Piltun-Astohskoye and Lunskoye oil and gas field during joined action of waves and currents

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The paper suggests a procedure for evalution of local scours in front of large Gravity Based Structures (GBS) under joined effect of waves and currents. Given are expressions and relationships for determination of scour depths. Results of evalution of local scours near GBS for the two "Sakhalin-II" locations, site "Piltun-Astohskoye" and site "Lunskoye", is presented as an example.

INTRODUCTION

Gravity Based Structures (GBS), installed at the sea bottom are known to substantially affect the wave pattern together with the superimposed flows. Vortex zones appear in the vicinity of the structure and the summary velocities of flow particles usually tend to surpass the critical values for various bed soils. As a result, local scours are appearing at the substructure units and this is leading to deterioration of normal operating conditions.

Judging from the consequences, two main failure models of soil foundation were selected for a structure during seabed scour. In the first case the holes appear directly near the borders of the GBS. If the height of a protective skirt is insufficient then intensive washing out of soils begins below the foundation resulting in additional deposits and tilts of the structure. The washing out of this kind is not admissible and accordingly the depths of local scours abutted to the GBS should not be more than the height of the skirt (usually 2.0-2.5 m).

In the second case the seabed scours occur at a distance from the structure and are not influenced directly by the contact of GBS with the soil but they sufficiently decrease stability of the soil foundation to shear. To estimate the marginal resistance to shear it is required to have information about dimensions in plan and depths of local scours.

At present the task of defining local scours near GBS with cross sections of large size under joint action of waves and current is far from final solution. Only separate publications are known, which are based on the results of laboratory researches of local scours near some types of structures basically from current [1 – 3 etc.] and also both from separate and joint action of waves and current [4 – 7]. The results of experimental researches of local scours of seabed at a barrier of the large cross sections and partial height in conditions of the North Sea are presented in work [2].

The review and the analysis of the relevant literature indicates that the problem of assessment of local scours, even at the simplest vertical cylindrical substructure units has no exact theoretical solution. All the known publications are mainly based on the data of laboratory tests. The performance of such tests presents difficulties of modelling structurally non-uniform foundation soils and especially their grain-size analysis.

METHOD PROPOSED

The authors of the present publication suggest the following set of special approaches for the determination of local scours at the substructure units of ice resistant structures. First, the locations of most intensive local bed scours (accounting for joint action of waves and flows) are identified in the laboratory on a physical model. Subsequently, the maximum bed velocities are determined in places most vulnerable to scours. Then the suggested engineering expressions are used for the evaluation of depths of local scours (with account of the known elements of waves and flows, characteristics of soil conditions and parameters of lithodynamic processes, known dimensions of substructure foundation, design of bed scour protection arrangements, etc.). Finally, the obtained data is compared with the permitted values (e.g. with the design height of stone layer).

Depths of local scours under the joint action of waves and currenst

Calculation of depth d_s of local seabed scour at depth of water d under the joint action of waves and currents was carried out on the proposed in [1, 2] general approach based on the following formulation:

$$d_S/d = f(t)\prod_{1}^{6} f_i, \qquad (1)$$

where $f(t)$ – the function accounting for changes of local scour depths with time,

$$f(t) = 1 - \exp(-t/A), \qquad (2)$$

$$A = 0,2 + 60 d_{50}, \qquad (3)$$

t – time, hour; d_{50} – sediment size by which 50% by weight is finer than, м.

For function f_1, accounting for the influence of waves on scour depth the following formula is proposed [7]

$$f_1 = 0,044\mathrm{KC}^*, \qquad (4)$$

where KC* – the modified Keulegan-Carpenter number is calculated by

$$\mathrm{KC}^* = \frac{V_w T_w}{d}. \qquad (5)$$

Here V_w – the maximum horizontal component of orbital wave velocity at a level of seabed; T_w – waves period accepted equal to average period of waves T_{av}; d – water depth.

The function f_2, accounting for the influence of current on scour depth is to be defined by formula [8]

$$f_2 = \frac{a \tanh\left[3,5\left(V_{cw} - b\right)\right] + 1,9 - a}{a \tanh\left(-3,5b\right) + 1,9 - a}, \quad (6)$$

$$a = \frac{0,95}{1 + 0,005\mathrm{KC}},\ b = \frac{0,8}{1 + 0,005\mathrm{KC}^2}, \quad (7)$$

$$\mathrm{KC} = \frac{V_w T_w}{D}, \quad (8)$$

where D – characteristic length of the structure, V_{cw} – effective dynamic flow velocity should be defined according to formula [9]

$$V_{cw} = \sqrt{\lambda/2}\left(V_c + \alpha_w V_w\right). \quad (9)$$

Here λ – the coefficient of hydraulic friction,

$$\lambda = 8\mathrm{g}/C^2, \quad (10)$$

where g – acceleration of gravity, C – Shezy coefficient determined according to formula [4]

$$C = 5.75\sqrt{g}\log_{10}\left(\frac{12d}{k_S}\right), \quad (11)$$

where k_S – equivalent roughness height,

$$\left.\begin{array}{ll} k_S = 2d_{50} & \text{for smooth conditions} \\ k_S = 3d_{90} & \text{for rough conditions} \end{array}\right\}, \quad (12)$$

where d_{50} and d_{90} – sediment size by which 50% and 90% by weight is finer than, m.

In the formula (9) also it is accepted: V_c – averaged in depths current velocity; α_w – the coefficient accounting for pulsation character of wave velocities at a level of seabed.

The coefficient α_w should be defined according to condition of equivalence of scour ability of wave and current,

$$\alpha_w = \frac{V_{cr,c}}{V_{cr,w}}. \quad (13)$$

Here $V_{cr,c}$ – critical flow velocity for current above homogeneous non-cohesion soil foundation defined by formula [10]

$$V_{cr,c} = \log\left(\frac{8.8d}{d_{50}}\right)\sqrt{\frac{2}{0.44k_n\rho_w}\left[\left(\rho_s - \rho_w\right)gd_{50} + 2c_y k_0\right]}, \quad (14)$$

where k_n – the coefficient accounting the pulsation character of current velocity within the seabed is defined by formula

$$k_n = 1 + \frac{1}{0.3 + \left(\frac{\nu^2}{gd_{50}^3}\right)^{1/3}}, \quad (15)$$

ρ_w – water density, ρ_s – soil density, c_y – fatigue rupture strength for non-cohesion fine-grained soil,

$$c_y = 8\rho\nu\frac{\left(g\nu\right)^{1/3}}{d_{50}}, \quad (16)$$

k_0 – the coefficient accounting for deviation of cohesion forces from their average values (it is possible to take $k_0 = 0.5$).

In the formula (13) also it is accepted: $V_{cr,w}$ – critical flow velocity for wave above homogeneous non-cohesion soil foundation defined by formula [11, 12]

$$\left.\begin{array}{ll} V_{cr,w} = 3.25\sqrt{gd_{50}} & \text{for } d_{50} < 3.38\times10^{-3} \\ V_{cr,w} = 3.25\sqrt{gd_{50}}\left(\frac{3.38\times10^{-3}}{d_{50}}\right)^{0.17} & \text{for } d_{50} \geq 3.38\times10^{-3} \end{array}\right\}. \quad (17)$$

The function f_3, accounting for the influence of the critical flow velocity for wave on the soil foundation is to be defined by formula [1, 2]

$$f_3 = \frac{V_{cw}}{V_{cr}^*}, \quad (18)$$

where V_{cr}^* – critical dynamic flow velocity for wave,

$$V_{cr}^* = \frac{V_{cr,w}\sqrt{g}}{C}. \quad (19)$$

The function f_4, accounting for the influence of the structure height on scour depth is recommended in [2] to take equal to 1 for $h_{pr}/d \geq 1$, where h_{pr} is the structure height above the seabed level, and for $h_{pr}/d < 1$

$$f_4 = \tanh\left[3,5V_{cw}\left(\frac{h_{pr}}{d} - 1,4\right)\right] + 1. \quad (20)$$

The function f_5, accounting for the influence of the structure shape on scour depth is to be taken in [2]: for circular structures – 1,0; for a square structures (90° orientation) – 2,0; for a square structures (45° orientation) – 2,8.

For the function f_6, accounting for the influence of the relationship of characteristic length of the structure D to water depth d, the following relation is recommended [1]:

$$f_6 = 1,5\left(D/d\right)^{0,65}. \quad (21)$$

The analysis of the scour depths according to (1 – 21) is based using a number of assumptions: directions of waves and current are accepted agreed; seabed soils are considered homogeneous, non-cohesion and nonlaminar in occurrence; the form of GBS is assumed symmetrical relative to the longitudinal axis; slope of the head edges of GBS are not considered.

VALIDATIONS

The developed fotmulas to predict the scour depth has been verified with other relevant data sets available. They are summarised in Table I, Table II.

TABLE I. VALIDATION DATA FOR CYLINDER WITHOUT CURRENT FROM [13]

Region of Russia	D, m	d, m	Boundary conditions			Scour depth d_s, m	
			H_w, m	T_w, s	d_{50}, m	Calc.	Meas.
Sea of Azov	8.0	5.5	1.4	5.0	0.00007	1.0	1.5
	8.0	5.5	2.0	5.0	0.00007	1.7	
	8.0	5.5	2.2	5.0	0.00007	2.1	
Black Sea	1.2	3.0	1.0	4.0	0.00020	0.6	0.6

TABLE II. VALIDATION DATA FOR GBS WITH CURRENT FROM [2]

GBS	D, m	d, m	Boundary conditions				Scour depth d_s, m	
			H_S, m	T_P, s	d_{50}, m	V_c, m/s	Calc.	Meas.
F3	80.0	42.3	9.5	13.3	0.00015	0.64	3.0	3.0
F3	80.0	42.3	9.5	13.3	0.00015	0.82	4.0	

It can be concluded that for both model and prototype data are within 20%. These results confirm the reliability of the developed fotmulas to predict the scour depth, although the amount of data is very limited.

PRACTICAL APPLICATIONS

This section presents the information about the results of test verification of constructions for scour protection of bottom soils under simultaneous action of waves and currents used in the projects of reinforced concrete gravity substructures for the GBS "Piltun-Astokhskoye B" (PA-B) and GBS "Lunskoye A" (Lun-A) at the licensed sites of the "Sakhalin-II" Project (Fig. 1).

The main goal of this results is to make expert estimation of the accepted constructions for scour protection of bottom soils under simultaneous action of waves and currents in compliance with the data received from the Russian designing practice.

The basic initial data used in designing and verification of constructions for scour protection of bottom soils around the substructures of the GBS PA-B and GBS Lun-A are presented in Table III.

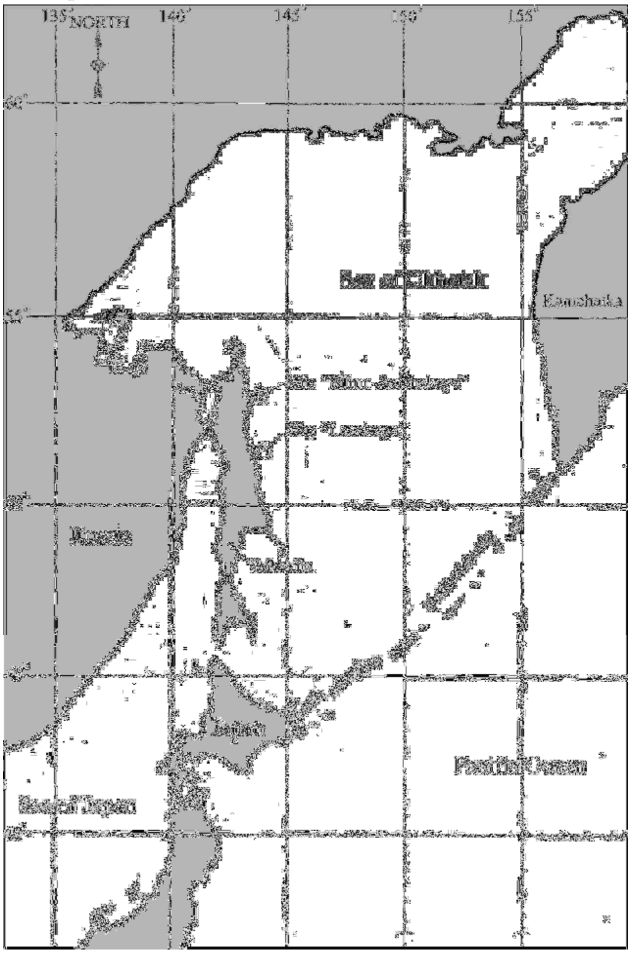

Figure 1. Situational scheme of site "Piltun-Astohskoye" and site "Lunskoye"

TABLE III. INITIAL DATA FOR DESIGNING AND VERIFICATION OF CONSTRUCTIONS FOR SCOUR PROTECTION OF BOTTOM SOILS AROUND OF THE GBS PA-B AND GBS LUN-A

GBS	PA-B	Lun-A
Sea depths		
Maximum sea depth (m)	34.78	53.63
Minimum sea depth (m)	29.50	47.70
Elements of waves independently of the angle of their approach in a storm of a 100 year return period		
Maximum wave height H_{max} (m)	18.0	18.8
Height of significant waves H_s (m)	9.7	9.9
Height of mean waves H_{av} (m)	6.1	6.2
Period of maximum waves T_{max} (s)	13.5	13.6
Spectrum peak period T_p (s)	14.2	14.3
Mean wave period T_z (s)	10.6	10.6
Velocities of currents of a 100 year return period independently of their direction		
On water surface (m/s)	1.78	1.59
At mid depth (m/s)	1.61	1.44
1 m above seabed (m/s)	1.07	0.91
Bottom soils		
Upper layer	Sand of average density, d_{50} = 0.30 mm	Sand: fine, medium, loose and of average density, d_{50} = 0.20 mm
Thickness of upper layer	Up to 0.5 m	Up to 0.8 m
Underlayer	Sand: fine, medium, hard with streaks of clay and gravel inclusions in the bottom of the layer d_{50} = 0.70 mm	Clay with streaks of silty and sandy soils
Thickness of underlayer	Up to 23.0 m	Up to 8.0 m

Platform descriptions

1) PA-B Platform

The PA-B combined drilling/production topside facilities will rest on a GBS at site "Piltun-Astohskoye". The base of the GBS PA-B consists of a concrete base caisson of 94 m x 91.5 m and 11.5 m in height (Fig. 2). Four conical concrete shafts rise 39 m in height from the base caisson to support the topside facilities.

2) Lun-A Platform

The Lun-A combined drilling/production topside facilities will rest on GBS at site "Lunskoye". The base of the GBS Lun-A consists of a concrete base caisson of 105 m x 88 m and 13.5 m in height (Fig. 3). Four conical concrete shafts rise 55.7 m in height from the base caisson to support the topside facilities.

Maximum bed wave velocities

Wave velocities around the faces of the support caissons of the platforms were observed near vertical walls of restricted width and incomplete height at the arbitrary angle of approach of interfered waves with allowance for non-linear effects by the 3rd order of approximation (3-D problem) [14].

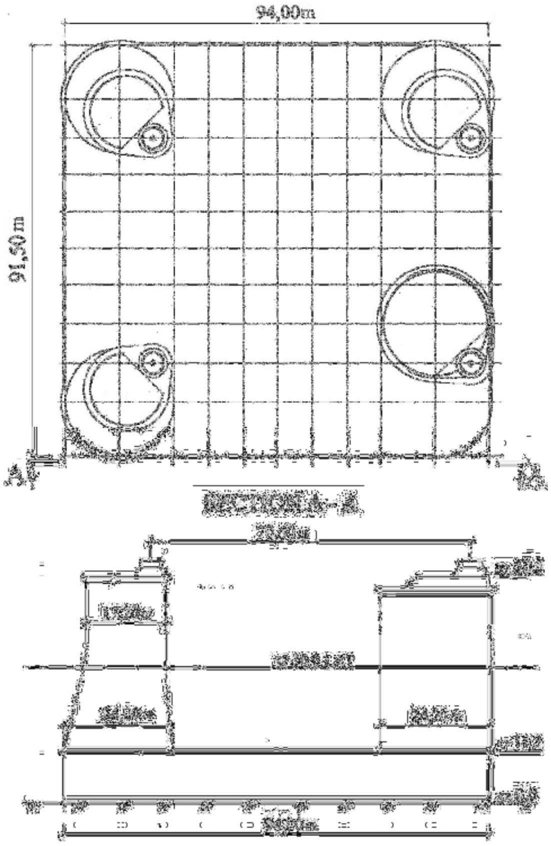

Figure 2. Plan and cross section of the substructure of the GBS PA-B

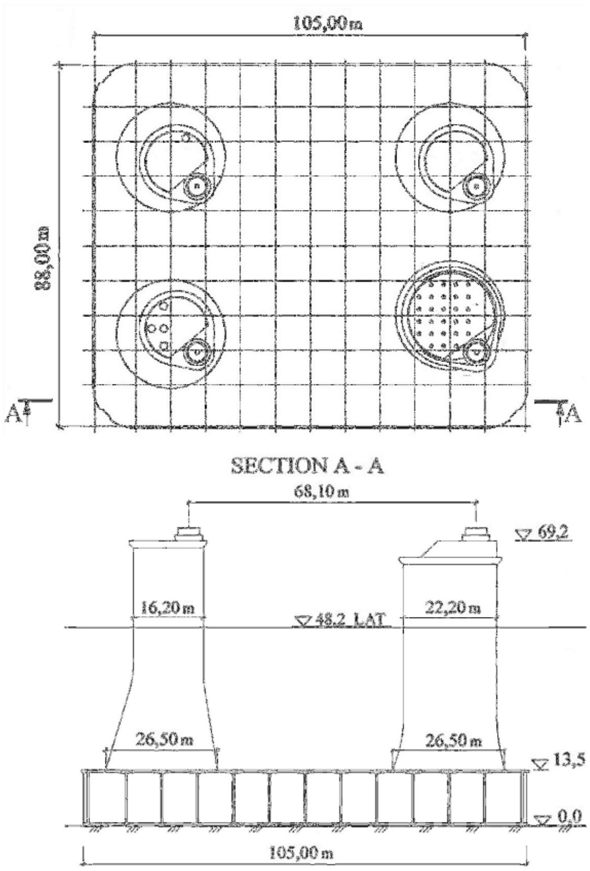

Figure 3. Plan and cross section of the substructure of the GBS Lun-A

Tables IV and V show the results of wave velocities at the seabed level near the front faces of the support caissons of the GBS PA-B and GBS Lun-A along the axis and at the corners of the vertical walls of restricted width and incomplete height with frontal approach of interfered waves with allowance for non-linear effects by the 3rd order of approximation.

TABLE IV. WAVE VELOCITIES ALONG THE AXIS OF THE GBS PA-B AND GBS LUN-A

Distance from frontal face along platform axis, m	Wave velocities around GBS, m/s	
	PA-B	Lun-A
1.0	1.05	0.82
5.0	1.05	0.82
15.0	1.20	0.88
20.0	1.30	0.93

TABLE V. WAVE VELOCITIES AT THE CORNERS OF THE GBS PA-B AND GBS LUN-A

Distance from the corners of the GBS, м	Wave velocities around GBS, m/s	
	PA-B	Lun-A
1.0	1.53	1.08
5.0	1.53	1.08
15.0	1.53	1.08
20.0	1.53	1.08

The results of calculation of local scour depths of bottom soils by the method according to the formulas (1 – 21) with the account of the combined effects of waves and currents are presented in Table VI.

TABLE VI. DEPTH OF SCOUR PITS IN BOTTOM SOILS AROUND THE GBS PA-B AND GBS LUN-A

Method	Depths of local scour in bottom soils around GBS, m	
	PA-B	Lun-A
Formulas (1 – 21)	8.43	4.86

The depths of local scour determined by the formulas (1 – 21) under simultaneous action of waves and currents exceed considerably the thickness of upper layers of bottom soils. This fact confirms that it is necessary to protect the seabed around the GBS PA-B and GBS Lun-A from scour.

From the data of the projects it follows that after installation of the platforms on the spot it is planning to erect protection fillings around the perimeter of the support caissons from stone with average size d_{50} = 0.25m with layers of 2.5 – 3.5m thick for the GBS PA-B and 2.0m for the GBS Lun-A. The width of the bottom of the protection filling makes up about 19.0m for the GBS PA-B and 15.0m for the GBS Lun-A. The filters from broken stone with average size d_{50} = 0.04m, 0.5m thick are arranged between the stone protection fillings and the seabed. The width on the bottom of the reverse filters makes up about 21.0m for the GBS PA-B and 17.0m for the GBS Lun-A.

The depths of local scour in the upper layer of the protection fillings calculated by the method according to the formulas (1 – 21) with the account of simultaneous action of waves and currents are presented in Table VII.

TABLE VII. DEPTHS OF SCOUR PITS AROUND THE GBS PA-B AND GBS LUN-A

Method	Depths of local scour of stone layer around GBS, m	
	PA-B	Lun-A
Formulas (1 – 21)	0.18	0.12

From the analysis of the data of Table VII it may be concluded that the accepted in the project protection filling with the stone size d_{50} = 0.25 m for the GBS PA-B and for the GBS Lun-A it is sufficient.

CONCLUSION

On the basis of the work presented in this paper the following is concluded and recommended:

- The improved design formulas has been offered for offshore structures subjected to wave or joined effect of waves and currents.
- Using the formulas the maximum local scour depths can be predicted.
- The design size of the constructions for scour protection for the GBS PA-B and GBS Lun-A are as a whole substantiated and valid.

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