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The formation of the seabed surface relief near the gravitational object

Формирование рельефа донной поверхности у гравитационного объекта

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Ключевые слова: гравитационное сооружение; течение; волнение; судовые волны; песчаные волны; интерференция

Abstract. During the interaction of waves and currents with objects established in the shallow offshore areas, scour of their base may occur. At the same time, it is always necessary to exclude the appearance of significant seabed scour near supporting parts of gravity-type platforms during the process of their design. The article presents the results of experimental studies of processes occurring under the impact of flows of various types on gravity-type structures and their foundations. The model of Prirazlomnaya platform and the model of drilling barge, which were performed on a scale of 1:60, were used as typical models of offshore structures of gravitational type. Analogies between ship and sand waves are revealed, conditions of appearance of soil waves interference from the rear face of platforms are analyzed.

Аннотация. При взаимодействии волн и течений с объектами, установленными на мелководных участках шельфа, может происходить размыв их основания. При проектировании платформ гравитационного типа необходимо исключить возникновение значительного размыва дна вблизи их опорных частей. В статье представлены результаты экспериментальных исследований процессов, происходящих при воздействии потоков различного типа на гравитационные сооружения и их основания. В качестве типовых моделей шельфовых сооружений гравитационного типа были использованы модель платформы «Приразломная» и модель буровой баржи, выполненные в масштабе 1:60. Выявлены аналогии между судовыми и грунтовыми волнами, проанализированы условия возникновения интерференции грунтовых волн со стороны тыльной грани платформ.

1. Introduction

Gravity-type platforms are one of the most common types of hydraulic engineering structures for the offshore development. The possibility of formation and development of local scour has to be considered during the process of platforms design. The identification of the basic mechanisms underlying the processes that occur in the water flow around hydrotechnical structures and its consideration during

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design should reduce the risks of emergencies and increase the safety of operation of the offshore objects [1–5].

Sand waves are the most common factor in the formation of the seabed surface relief in shallow water [6–9]. Two types of sand waves with different reasons of formation on an underwater slope in the vicinity of the location of a large-scale gravity-type object are distinguished in this article. An object whose characteristic linear dimension (for example, the width *B* or the length *L* of the object) is greater than the depth of water *d* in the place of its location will be called an object of large size.

The possibility of formation of sand waves like a transverse ship waves is the first occasion identified in this study. As it is known, ship-induced waves are formed when a partially submerged vessel moves in calm water. Divergent and transverse waves are formed in this case [10, 11]. Divergent waves form an echelon of waves approximately parallel to each other, originating in both the bow and the stern of the vessel. Transverse waves are formed along the vessel at the bow and stern parts of the sides, as well as behind the stern. The group of transverse waves formed in the bow begins with the crest of the wave, and the group formed in the stern part begins from the trough. Such waves can be obtained according to the principle of motion relativity if the vessel is stationary and the flow of water will be uniform. Formation of sand waves like a ship's waves is possible in the case under consideration when the stream of water-saturated soil flows around stationary gravitational object and along its sides.

The second case is the formation of forced sand waves arising in consequence of the transfer of part of the water flow energy to the seabed surface causing a certain movement of seabed soil particles. Periodic structures (sand waves) are formed on the seabed surface and move along the underwater slope at a certain rate because of this displacement of soil particles.

A large object located on the underwater slope under its own weight, for example, a gravity platform, interacts with both the water flow and the flow of seabed soil moving along the underwater slope. Thus, in this case, the seabed surface relief formation occurs as a result of the development of all the above-mentioned sand waves.

2. Methods

Experimental investigations were held in order to obtain and analyze information on changes in the relief of the seabed surface caused by the frontal water flow formed by regular waves and currents impact on the gravity-type platforms [12–15]. It was assumed that the frontal action of the water flow on the platform is carried out during one design storm; the slope of the seabed surface in the vicinity of the platform was assumed to be zero before the start of the experiment; the current during the considered period of time is assumed to be constant; there are no suspended sediments in the water flow approaching to the considered seabed surface.

Experimental studies of the seabed surface relief changes in the gravitational-type model location caused by the frontal action of regular waves and currents were performed on an experimental setup that was organized using the enclosing working area inside the test basin (with overall dimensions 40.0 × 6.2 m). Waves were generated by a mobile beam-type wavemaker with a beam length of 6.1 m, which was placed on the basin floor at 7 m from the outlet of water supply to the test setup. At 17 m from water supply outlet, a test area began in a form of underwater ledge with height from the basin floor equal to 0.4 m and with length equal to 12 m (Figure 1). In the middle of the ledge, a test section was placed measuring 4.0 × 4.0 × 0.4 m, which was filled with fine-grained sand with average diameter of particles equal to 0.22 mm (Table 1). The sand was wetted and compacted. The sand surface top level was constant everywhere and equal to 0.4 m from the basin floor. In the center of the test section, the models made of bakelite plywood were placed on rigid base with the level that was accurately equal to 0.4 m with respect to the basin floor. The rest of the ledge is covered with bakelite plywood. The pipe 0.1 m diameter with removable plug on the upper side was laid on floor along the basin wall for convenient filling of the experimental setup with water (Figure 1).

Table 1 – Granulometric composition of sand used in the experimental studies in percentage, the shape of the grain is semicircular

Sieve size									
0.63	0.4	0.315	0.2	0.16	0.1	0.063	0.05	Residual	Clay
0.40	6.40	16.20	44.80	15.80	9.94	4.86	0.50	0.40	0.86

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At a distance of 11 m from the test area with the flow, a metal wall was established (Figure 1) in which, up to a mark of 0.45 m relative to the basin bottom, two rectangular spillways each 1.2 m wide were cut.

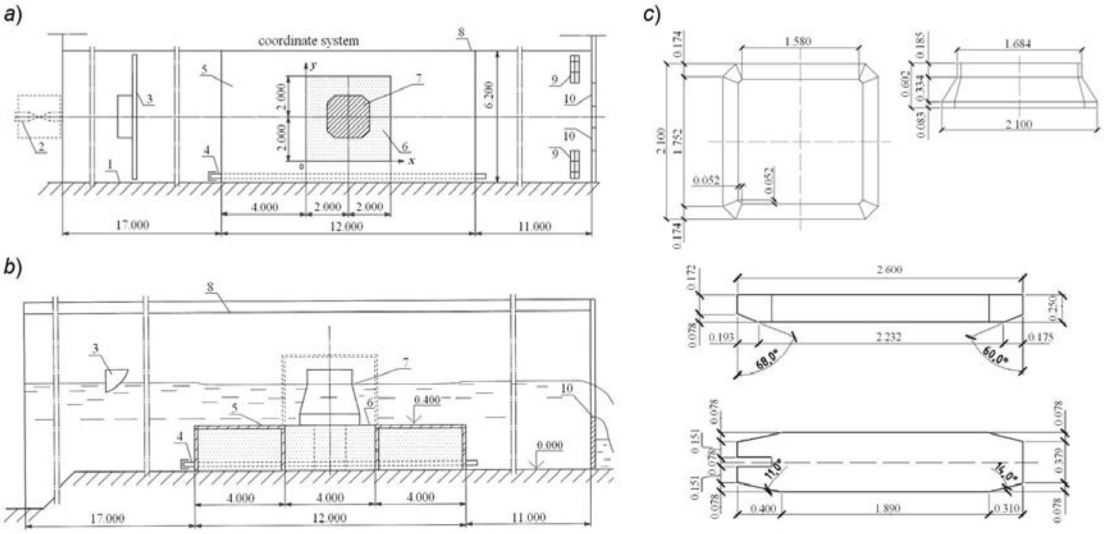

Figure 1. Test setup:
a **– plan;** ***b*** **– longitudinal section;** ***c*** **– gravity-type Platform and Barge models:**
1 – wave basin wall; 2 – supply pipeline with stop valve; 3 – beam-type wavemaker;
4 – pipeline with plug; 5 – test area; 6 – test section; 7 – platform model; 8 – enclosure;
9 – wave suppressor; 10 – weir with thin wall

Thus, two thin-plate weirs were formed. The marks of the weirs crests were variable and were established depending on the conditions of the experiments. These weirs were used to determine the average water flow velocity V. The inclined wave suppressors were installed before the metal wall of the enclosure and from the side of the pool wall (Figure 1). The water supply to the experimental setup was carried out by a centrifugal pump from an underground reservoir through a system of pipelines and valves. A valve installed before experimental facility regulated the change in flow rate. As exemplary models of the gravity platforms, the model of the offshore ice-resistant fixed platform Prirazlomnaya (hereinafter referred to as the Platform) and the model of the drilling barge (hereinafter referred to as the Barge), made on a scale of 1:60, were used.

Physical modeling of the processes of seabed surface changing near the gravity-type platforms under the impact of the water flow formed by waves and current was carried out on the assumptions that the motion of the water and soil flows satisfies the Navier-Stokes equations and that modeling should be conducted without distortion of scales, geometric similarity, both artificial structures, and parameters of water flows in order to obtain a qualitative correspondence between the processes taking place in nature and on the model. In the described studies, the modeling of the soil composing the seabed was carried out by fine-grained sand with an average particle diameter of 0.22 mm.

The kinematic similarity of the occurring processes was due to the equality in the model and in nature of the Froude numbers $\mathrm{Fr}_V = V^2 \big/ gd$ that were determined with respect to the depth *d* and the average flow velocity V of the water flow acting on the object.

In order to study the beginning of the formation of the seabed relief of the underwater slope in the intended conditions of the action of the water flow on the gravity-type platform, experimental studies were carried out at values of the Shields parameter θ less than the critical ones (Table 2).

To fulfill this condition, the values of the Shields parameter were calculated by the formula

$$\theta = U_f^2 \big/ \left(g\left(\rho_s - \rho\right) D_0 \right),$$

where U_f is the dynamic velocity; ρ_s is the density of the particles of the soil composing the seabed; ρ is the density of water.

At the same time, the values of the Reynolds number for the dynamic velocity were calculated from expression

$$\mathrm{Re}_f = U_f D_0 / \nu ,$$

where ν is the kinematic viscosity of water.

The relationship between U_f and the velocity of the water flow $U = \left(V + U_{w_{\max}}\right)$ was taken in the following form [16]:

$$U_f = U\sqrt{f/2} ,$$

where f is the coefficient of hydraulic friction; $U_{w_{\max}}$ is the maximum orbital velocity in the wave.

The hydraulic friction coefficient for water flows formed by waves and currents moving above the eroded seabed was determined as follows accordingly to [17]:

$$f = \left(f_c^2 V^2 + f_w^2 U_{w_{\max}}^2\right) \Big/ \left(f_c V^2 + f_w U_{w_{\max}}^2\right),$$

where f_c is the coefficient of hydraulic friction for the water flow moving above the eroded seabed with an average velocity (it was determined according to [18]); f_w is the coefficient of hydraulic friction for the water flow formed by waves with the maximum orbital velocity $U_{w_{\max}}$ moving above the eroded seabed (its value was determined according to [16, 17, 19]).

Table 2. Conditions of tests

Test No.	**Water depth *d*, m**	**Average speed of current *V*, m/s**	**Wave height, *h*, m**	**Wave period *T*, s**	**Froude number Fr_V**	**Reynolds number Re_f**	**Shields parameter *θ***
1	0.330	0.067	0.053	1.7	0.0014	2.07	0.012
2	0.330	0.067	0.095	1.7	0.0014	4.08	0.029
3	0.175	0.125	0.074	1.7	0.0091	3.24	0.089
4	0.175	0.125	0.064	1.7	0.0091	2.14	0.022
5	0.330	0.067	0.095	1.3	0.0014	3.86	0.060
6	0.330	0.067	0.107	1.3	0.0014	3.60	0.080
7	0.160	0.105	0.068	1.3	0.0070	3.57	0.042
8	0.175	0.124	0.080	1.3	0.0090	3.88	0.049
9	0.162	0.108	0.081	1.3	0.0073	4.21	0.060
10	0.177	0.129	0.065	1.3	0.0096	2.84	0.026

The values of the Shields parameter calculated for the conditions of carried out experimental studies were sufficiently close to the critical values determined for the corresponding Reynolds numbers Re_f from the Shields curve given in [20].

The experimental setup was drained and the formed bottom relief was fixed using the GOM ATOS 2 Triple Scan measuring information system after the end of each of the tests. The cloud of coordinates of the points obtained during each experiment was used to measure the relief plan of the seabed surface and to measure its profiles in the intended cross sections [12, 14, 15].

3. *Results and Discussion*

The frontal impact of the water flow formed by regular waves and current on the gravity-type platform changes the seabed relief by forming the movement of sand waves on the bottom surface adjacent to the platform.

The stream around a gravity-type construction formed by a soil flow caused by the simultaneous frontal action of regular waves and currents contributes to the formation of sand waves of the ship waves type at the side faces of the object and behind its stern. The formation of these waves was observed both at the sides of the Platform model and at the sides of the Barge model (Figures 2–7, 9–12).

Analysis of the relief of the bottom surface formed as a result of experiment No. 1 indicates the presence of groups of sand waves at the side faces of the Platform (Figure 2). Groups of sand waves formed closer to the frontal face begin with a crest (area 1 in Figure 2), while groups of sand waves formed closer to the rear side begin with a trough (area 2 in Figure 2). The fronts of these waves are practically perpendicular to the direction of motion of the water stream. Thus, it can be argued that for the values of the water flow parameters in experiment No. 1 (Table 2), the movement of the bottom soil begins, in interaction with which lateral sand waves like a transverse ship waves begin to form at the lateral faces of the Platform. Behind the Platform, there is also the formation of a group of transverse waves (area 3 in Figure 2).

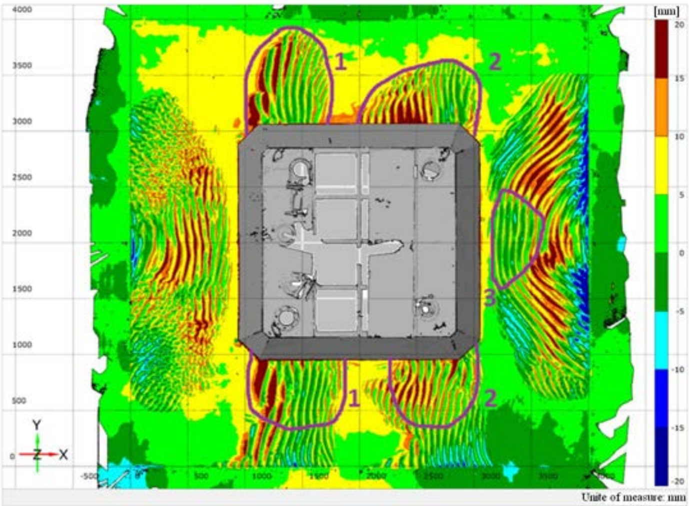

Figure 2. Bottom profile near the Platform model after experiment No. 1:
1 – formation of transverse sand waves at the bow parts of the side faces;
2 – formation of transverse sand waves at the stern parts of the side faces;
3 – formation of transverse sand waves astern of the Platform

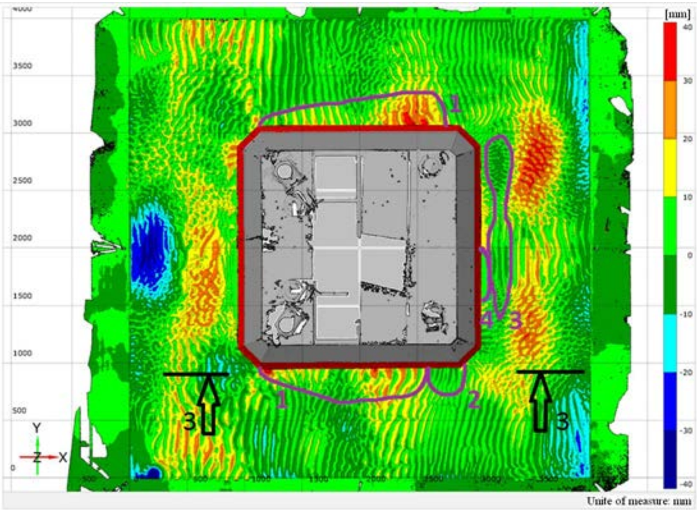

Figure 3. Bottom profile near the Platform model after experiment No. 2:
1 – formation of transverse sand waves at the bow parts of the side faces;
2 – formation of transverse sand waves at the stern parts of the side faces;
3 – formation of transverse sand waves astern of the Platform;
4 – not deformed seabed surface behind the stern of the Platform;
3-3 is a cross-section, through which the seabed surface profile is made shown in Figure 8

As the parameters of the water flow (wave heights and flow velocities) increase and, consequently, as growth in the parameters of the soil stream flowing around the Platform, the groups of transverse sand waves at the lateral sides merge near the frontal face with the formation of a common transverse sand wave with a complex-shaped crest (areas 1 in Figures 3–8). One or more crests of transverse waves (areas 1 in Figures 4–7) form at the frontal part of the Platform side faces depending on the nature of flow around. At the stern part of the Platform along the lateral faces, transverse waves begin to form, starting from the trough (areas 2 in Figures 4–7). Simultaneously, the water flow contributes to formation and movement of sand waves of shorter length along the side faces of the Platform along the resulting relief of the bottom surface (Figure 8).

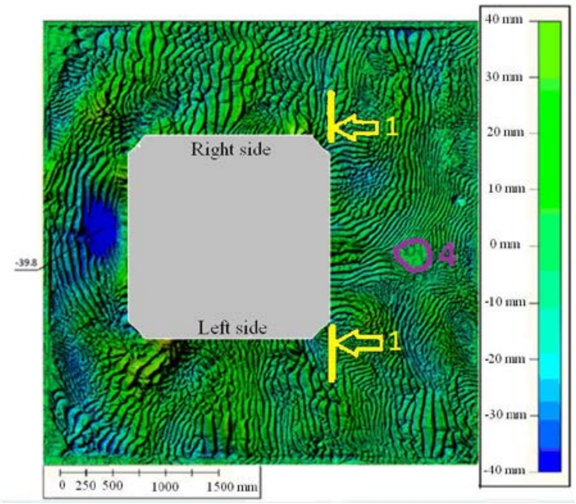

Figure 4. Bottom profile near the Platform model after experiment No. 3:
1 – formation of transverse sand waves at the bow parts of the side faces;
2 – formation of transverse sand waves at the stern parts of the side faces;
3 – formation of transverse sand waves astern of the Platform;
3-3 is a cross-section, through which the seabed surface profile is made shown in Figure 8

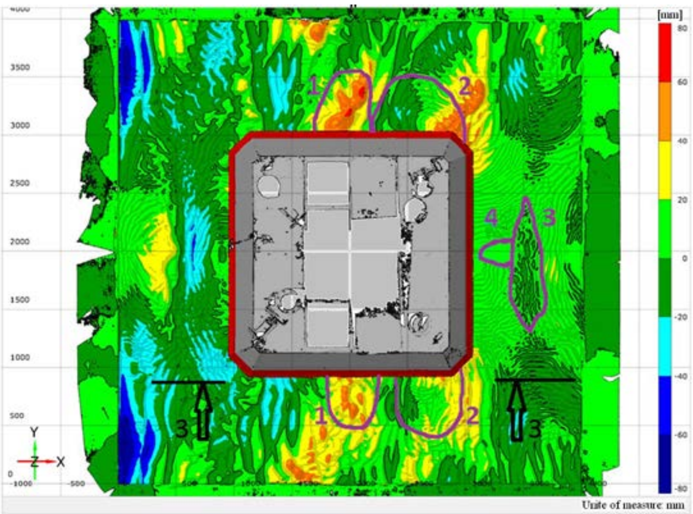

Figure 5. Bottom profile near the Platform model with a protective skirt with a length of penetration into the soil *H* = 0.20 m after experiment No. 4:
4 – not deformed seabed surface behind the stern of the Platform;
1-1 is a cross-section, through which the seabed surface profile is made shown in Figure 14

Figure 8 presents bottom surface profiles along the left lateral face of the Platform formed as a result of experiments NoNo. 2, 3 and 5 (cross-section 3-3 in Figures 3, 4, 6). The conditions for experiments NoNo. 2 and 5 are identical in depth and flow velocity of the water flow, as well as in the height of the generated regular waves, and differ only in the period of these waves (Table 2). The conditions of experiment No. 3 differed from the conditions for experiments NoNo. 2 and 5 (Table 2), only the period of regular waves was the same as in test No. 2. The distance *l* between the top of the first crest of the transverse sand wave in the bow part of the Platform and the maximum depth of the first trough of the transverse sand wave in the stern of the Platform, divided by the characteristic size of the

Platform, was selected as a characteristic value η_l to analyze the bottom surface profiles shown in Figure 8. In this case, the width *B* of the side face of the Platform is used (Figure 1), so $\eta_l = l/B$.

Consequently, $\eta_{l2} = 0.55$ for the experiment No. 2, $\eta_{l3} = 0.23$ for the experiment No. 3, $\eta_{l5} = 0.75$ for the experiment No. 3.

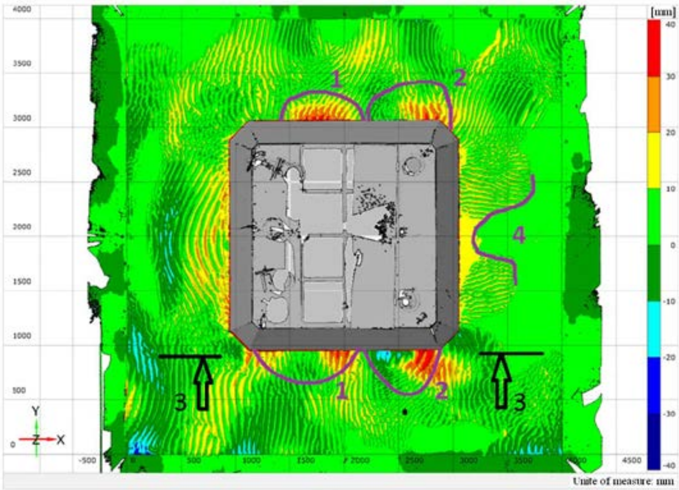

Figure 6. Bottom profile near the Platform model after experiment No. 5:
1 – formation of transverse sand waves at the bow parts of the side faces;
2 – formation of transverse sand waves at the stern parts of the side faces;
4 – not deformed seabed surface behind the stern of the Platform;
3-3 is a cross-section, through which the seabed surface profile is made shown in Figure 8

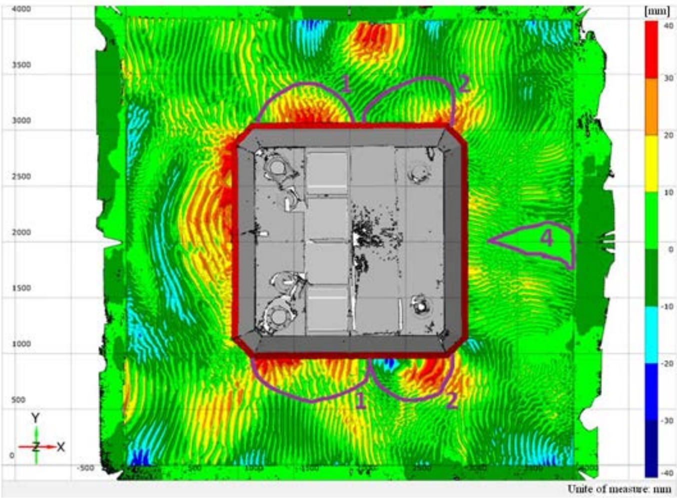

Figure 7. Bottom profile near the Platform model after experiment No. 6:
1 – formation of transverse sand waves at the bow parts of the side faces;
2 – formation of transverse sand waves at the stern parts of the side faces;
4 – not deformed seabed surface behind the stern of the Platform

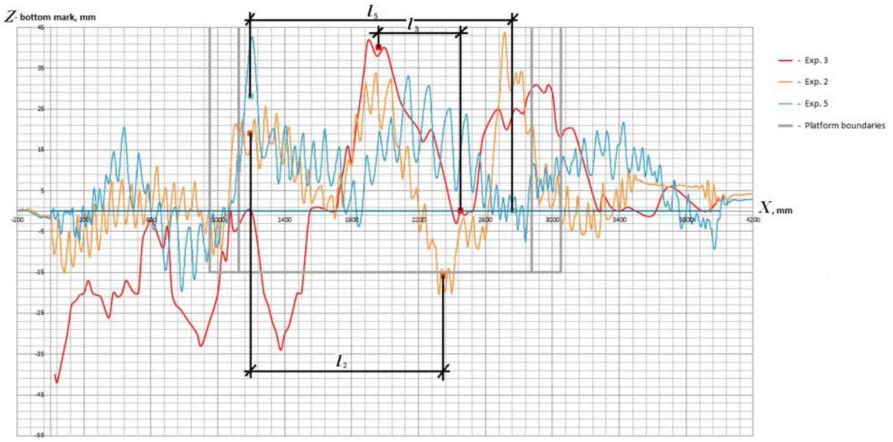

Figure 8. The profiles of the bottom surface along the left side of the Platform in the cross-section 3-3 along the side of the Platform model as a result of experiments NoNo. 2, 3 and 5

Analysis of the bottom surface profiles considered (Figure 8) and the values η_l obtained show that the magnitude η_l depends on all parameters of the water flow, but the value η_l is greater for larger sizes of the wave period, when all other parameters of the water flow are equal. It should be noted that when the parameters of the soil stream caused by the water flow increase, the first crest of the sand transverse wave is shifted toward the stern (comparison of the curves for the Experiments NoNo. 2 and 3 in Figure 8).

A similar relief of the bottom surface in the form of transverse sand waves is created along the lateral faces in the case of the frontal action of the water flow formed by regular waves and currents on a gravity platform of the Barge type (Figures 9–11). The formation of transverse sand waves in the bow parts of the Barge sides beginning at the crest (areas 1 in Figures 9–11) and at the stern parts starting from the trough (areas 2 in Figures 9–11) was also observed in this case. The flow around the Barge with a high parameters generate transverse waves with a common crest of a complex shape near the bow (areas 1 in Figures 9–11) and form transverse waves beginning with troughs with large depths at the stern part just as in the case of the flow around the Platform (areas 2 in Figures 9–11). Experiment No. 10 with the impact of the water flow formed by regular waves and currents on the Barge with protective underwater riprap prism showed that sandy transverse waves are formed along the sides as in the cases already considered (Figure 12).

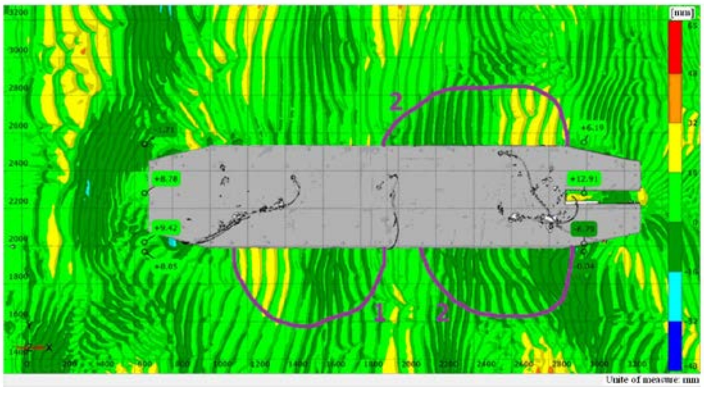

Figure 9. Bottom profile near the Barge model after experiment No. 7:
1 – formation of transverse sand waves at the bow parts of the side faces;
2 – formation of transverse sand waves at the stern parts of the side faces

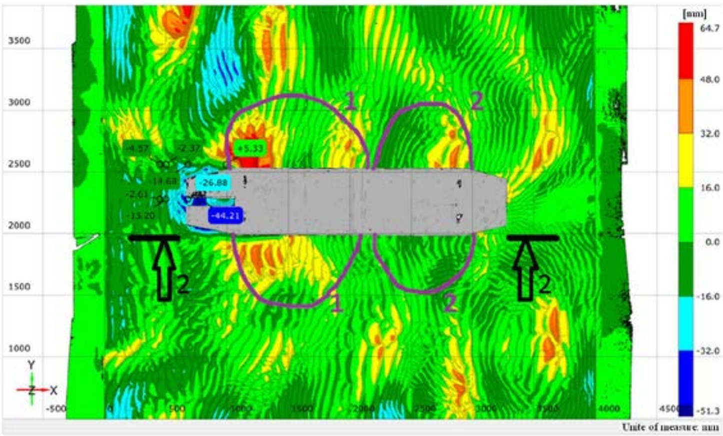

Figure 10. Bottom profile near the Barge model after experiment No. 8:
1 – formation of transverse sand waves at the bow parts of the side faces;
2 – formation of transverse sand waves at the stern parts of the side faces;
2-2 is a cross-section, through which the seabed surface profile is made shown in Figure 13

Figure 13 shows the bottom surface profiles along the side of the Barge (cross-sections 2-2 in Figures 10 and 11) formed as a result of experiments NoNo. 8 and 9. As it can be seen from Table 2, the conditions for experiments NoNo. 8 and 9 differ in the values of water depths and flow velocities, while the wave parameters (wave heights and periods) are practically the same.

The distance l between the top of the first crest of the transverse sand wave in the bow part of the Barge and the maximum depth of the first trough of the transverse sand wave in the stern of the Barge, divided by the length of the barge underwater base L, was selected as a characteristic value η_l to analyze the bottom surface profiles shown in Figure 13, so $\eta_l = l/L$.

Consequently, $\eta_{l8} = 0.54$ for the experiment No. 8 and $\eta_{l9} = 0.50$ for the experiment No. 9.

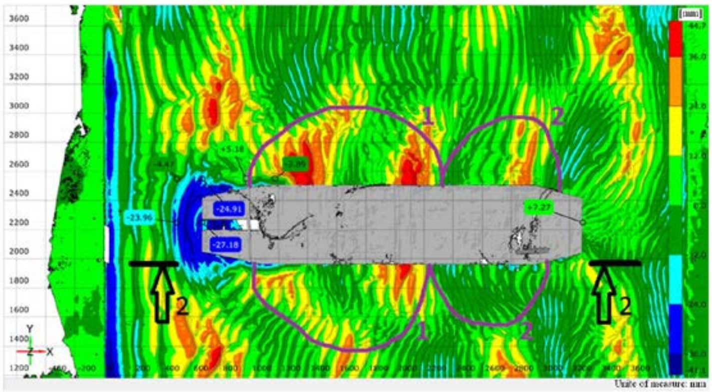

Figure 11. Bottom profile near the Barge model after experiment No. 9:
1 – formation of transverse sand waves at the bow parts of the side faces;
2 – formation of transverse sand waves at the stern parts of the side faces;
2-2 is a cross-section, through which the seabed surface profile is made shown in Figure 13

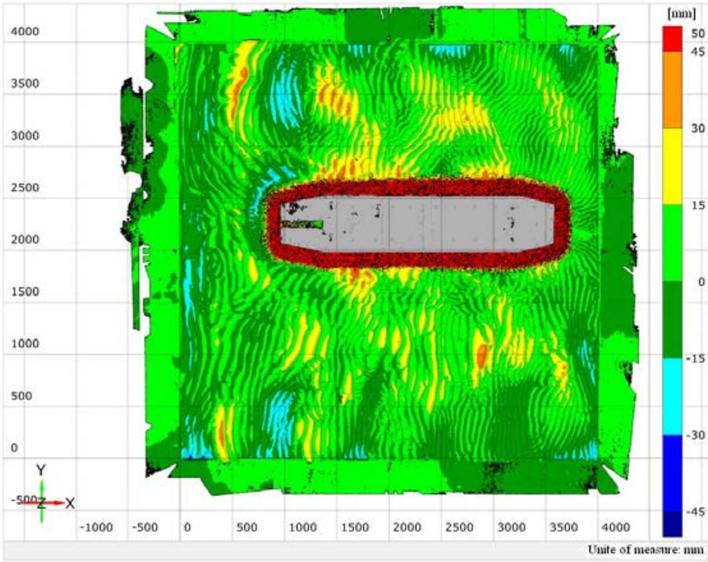

Figure 12. Bottom profile near the Barge model with protective underwater riprap prism after experiment No. 10

Analysis of the bottom surface profiles under consideration (Figure 13) shows that in the cases of water flow impact on the Barge, the values η_l for experiments NoNo. 8 and 9 remain close to each other, but at higher water flow velocities the value η_l will be greater.

Against the background of the formation of transverse waves similar to ship waves along the sides of the Barge, sand waves of smaller length are formed by the moving water flow just as in the experiments with the Platform (Figure 13). It should be noted that the flow around a large-sized object by the water stream generates movement of sand waves along the underwater slope that promotes the appearance of diffraction and interference of sand waves in specific areas near the object [21].

The interference of sand waves is a phenomenon of amplification or weakening of the amplitude of the resultant wave, depending on the relation between the phases of two sand waves forming in space or, in other words, the addition of several coherent oscillations of sand waves, in which they either strengthen or weaken each other [22, 23].

Sand waves move along the side faces of the Platform as already noted. The sand waves unfold at the cut corners and move along the back face (Figures 4–7). Sand waves from the left and right sides move towards each other along the back face. Interference of sand waves is possible in sum of these motions. The position of the interfered waves can be traced along the area of the unperturbed bottom surface, which divides the motion from the left and right sides.

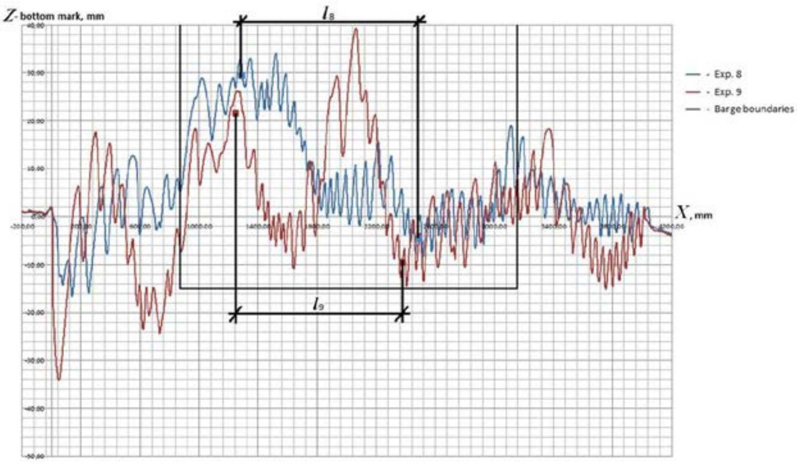

Figure 13. The longitudinal profiles of the bottom surface in cross-section 2-2 along the side of the Barge model as a result of experiments NoNo. 8 and 9

There will be an area of the unperturbed bottom surface (areas 4 in Figures 4, 6, 7) between the fronts of the sand waves moving both from the left and right sides of the Platform, if the energy of the water flow transmitted to the bottom surface is not sufficient to move sand waves along the entire length of its back face. The interaction of sand waves moving towards each other from the left and right sides does not occur. The interaction between sand waves moving from the left and right sides of the Platform is possible if this energy is sufficient (Figure 5). And if the rays of sand waves are parallel to the rear face, then interference occurs in the interaction area (Figure 14).

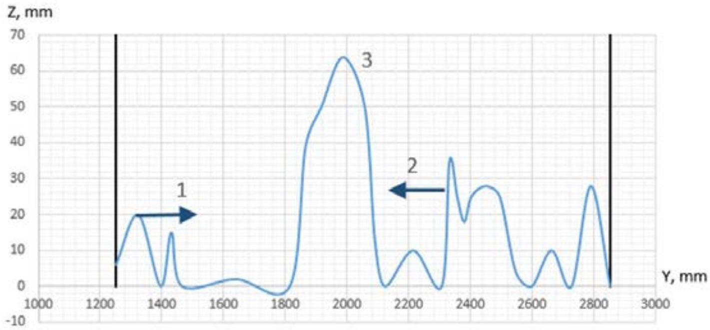

Figure 14. Interference (3) during the movement of sand waves (1, 2) along the rear edge of the Platform as a result of the experiment No. 4 (Cross-section 1-1 in Figure 5)

4. Conclusions

The presented results indicate that when interacting of a frontal water flow formed by regular waves and current with a gravity-type platform of a large size, the relief of the seabed surface adjacent to the platform is formed by sand waves.

The formation of sand waves is caused by the various reasons, among which it is necessary to allocate water and soil motion. Waves formed by soil flows are similar in nature to ship waves.

The ground flows moving around the platform contribute to the formation of larger waves, on which surface sand waves formed by the water flow move. Because of the movement of sand waves formed by the water flow, their interference behind the back of the platform is possible.

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