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Physical Modeling of the Effect of Tidal Sea Level Fluctuations on Wave-Absorbing Pebble Beaches

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Abstract
Implementation of coastal protection measures on the coasts of the Arctic and Far Eastern seas with tidal phenomena determines increased requirements for the justification of design solutions when developing schemes for engineering protection of the shores. Wave-absorbing structures, including wave-absorbing beaches consisting of coarse-grained material, are the most effective ones for protecting coasts from the effects of waves. This is particularly true for northern seas, coasts of which are perpetually frozen. The calculation of such beaches should take into account the effect of periodical sea level fluctuations on the formed profile. Field studies of the effect of tidal sea level fluctuations on the profile of a wave-absorbing pebble beach are associated with certain difficulties. The most promising are experiments performed on hydraulic models in wave pools and flumes. The purpose of the work is to study in a wave flume the effect of tidal cycles on the profile of a wave-absorbing pebble beach. It was found that during high tide, when the initial backfill is exposed to waves, a beach profile is formed similar to the profile generated at a constant level corresponding to the maximum phase of the tide. At low tide, the pebble is displaced by waves seaward of the underwater border of the pebble beach formed at a constant water level. At high tide, the displaced pebble does not completely return to the upper part of the profile, which leads to a decrease in the width of the surface part of the beach and that in its wave damping efficiency. Based on studies performed in seas with a tide height of up to 3.6 m, when creating wave-absorbing pebble beaches, the volume of the initial backfill of beach-forming material must be increased by 5 % compared to the volume calculated for tidal seas.

Keywords: beach profile, high tide, hydraulic modeling, low tide, wave absorbing pebble beach

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Физическое моделирование влияния приливных колебаний уровня моря на волногасящие галечные пляжи

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Аннотация

Проведение берегозащитных мероприятий на побережье арктических и дальневосточных морей с приливо-отливными явлениями определяет повышенные требования к обоснованию проектных решений при разработке схем инженерной защиты берегов. Для защиты берегов от воздействия волн наиболее эффективными являются волногасящие сооружения, включая и волногасящие пляжи из крупнообломочного материала. Особенно это актуально для северных морей, на берегах которых распространена вечная мерзлота. При расчете таких пляжей необходимо учитывать влияние периодических колебаний уровня моря на формируемый профиль. Исследования влияния приливо-отливных колебаний уровня моря на профиль волногасящего галечного пляжа в природных условиях сопряжены с определенными сложностями. Наиболее перспективными являются эксперименты, выполняемые на гидравлических моделях в волновых бассейнах и лотках. Цель работы – исследование в волновом лотке влияния приливо-отливных циклов на профиль волногасящего галечного пляжа. Получено, что во время прилива при воздействии волн на исходную отсыпку формируется профиль пляжа, подобный профилю, вырабатываемому при постоянном уровне, соответствующем максимальной фазе прилива. При отливе галечный материал смещается под воздействием волн мористее подводной границы галечного пляжа, сформированного при постоянном уровне воды. Во время прилива смещенный галечный материал не полностью возвращается в верхнюю часть профиля, что приводит к уменьшению ширины надводной части пляжа и снижению его волногасящей эффективности. На основании выполненных исследований на морях с высотой прилива до 3.6 м объем исходной отсыпки пляжеобразующего материала при создании волногасящих галечных пляжей необходимо увеличить на 5 % по сравнению с объемом, рассчитанным для бесприливных морей.

Ключевые слова: волногасящий галечный пляж, гидравлическое моделирование, отлив, прилив, профиль пляжа

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Introduction

The development of the northern seas resources is often associated with the implementation of coastal protection measures on their shores. Relatively low coastal areas composed mainly of easily eroded and perpetually frozen soils, and tidal phenomena determine the difficult natural conditions of the Arctic coasts. In this regard, increased requirements are imposed on the substantiation of design solutions in the development of engineering coastal protection schemes. The measures under development must totally meet environmental challenges and ecological requirements.

Under such unfavorable natural conditions, the most promising choice of coastal protection structures is the use of wave-absorbing permeable structures, such as berms made of stone or shaped solid monoliths, as well as the creation of wave-absorbing beaches filled with coarse-grained material, such as pebble or crushed stone. In this work, a wave-absorbing beach is a beach where the waves of the standard project storm are completely absorbed at a sea level of 1% probability.

The parameters of the profile of a wave-absorbing pebble beach formed under the influence of waves are basic for the calculation of the required volumes of dumped material. The method for determining the volumes of the initial dumping of the beach-forming material is based on the profile of relative dynamic equilibrium. This method is developed for tideless seas 1) with negligible sea level fluctuations [1]. In tidal seas, sea level fluctuations of significant amplitude should affect the formed beach profile. Under natural conditions, field studies of the dynamics of profiles of a wave-absorbing pebble beach complicated by the influence of periodic tidal fluctuations in sea level present certain difficulties, which make it impossible to identify the features of such profiles and their differences from profiles formed at a constant sea level. One of the most promising methods for such studies is hydraulic modeling in wave basins and flumes.

The purpose of this work is to identify the differences between the profiles of a wave-absorbing pebble beach formed by waves under conditions of sea level tidal fluctuations, and the profiles formed at a constant water level.

Materials and methods of studies

Published sources do not contain any information about the stability of a wave-absorbing pebble beach created to protect an eroded coast from the effects of waves under tidal conditions, and about the profiles of such a beach formed from the material of the initial backfill of beach-forming material. In this regard, in the wave flume of the Research Center “Sea Coast” (Sochi), the formation of profiles of a wave-absorbing pebble beach during sea level tidal fluctuations was studied and compared with the beach profiles developed at a constant water level.

The effect of tidal phenomena on the formation of the profile of a wave-absorbing pebble beach was evaluated based on the results of laboratory experimental studies in comparison with the data obtained at a constant water level in the wave flume, which was taken as the water level in the high tide maximum phase. In addition, the initial conditions for the experiments and the wave parameters remained unchanged. Studies of the dynamics of the profile of a wave-absorbing pebble beach, filled in front of the coastal ledge to protect it from the effects of waves, were carried out at the maximum wave parameters that can occur at high tide sea level. At the beginning of each series of experiments, studies of the beach profile formed at the constant maximum water level were carried out. After that, experiments were carried out on the formation of profiles of a pebble

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1) Smirnova, T.G., Pravdivets, Yu.P. and Smirnov, G.N., 2002. [*Coast Protection Structures*]. Moscow: Izd-vo Assotsiatsii stroitelnykh vuzov, 302 p. (in Russian).

beach during tidal cycles with different initial conditions for the impact of waves on the initial backfill of beach-forming material. Comparison of the results of experimental studies at constant and variable water levels made it possible to evaluate the effect of tidal phenomena on the formation of the profile of a wave-absorbing pebble beach.

The Froude number was used as the main criterion for the wind waves modelling 2) [2]. According to this criterion, the dimensions of the structures on the model, the depths and elements of the waves are taken on a linear scale. The time of wave impact on the studied beach model is determined taking into account the time scale equal to the square root of the selected model scale. At the same time, the duration of high and low tide in kind was taken equal to 12 hours. On the approaches to the beach, regular waves were reproduced. The scale of the model of the underwater slope and hydraulic structures was chosen based on the size of the reproduced bottom and wave elements. The bottom of the model should be made rigid; when it is rough, at least five wavelengths should be placed on it.

The wave heights on the model were measured by capacitive wave recorders DUE-1 with the processing of the measurement results on a computer, and also controlled by a ruler (Fig. 1).

Preliminarily, the wave height sensors were calibrated during their stepwise immersion to a certain depth. The recording of the excitement in the basin was accompanied by photography and video recording. The wavelength was recorded by shooting near the wave recorders against the background of a grid applied to the side wall of the flume.

According to the theory of similarity, it is necessary to study the process of wave impact on structures on a hydraulic model while ensuring the geometric similarity of the model to a full-scale object, the similarity of the wave regime, the similarity of surface and volume forces, i.e. it is necessary to ensure the equality of all defining criteria. In the general case, it is almost impossible to fulfill all

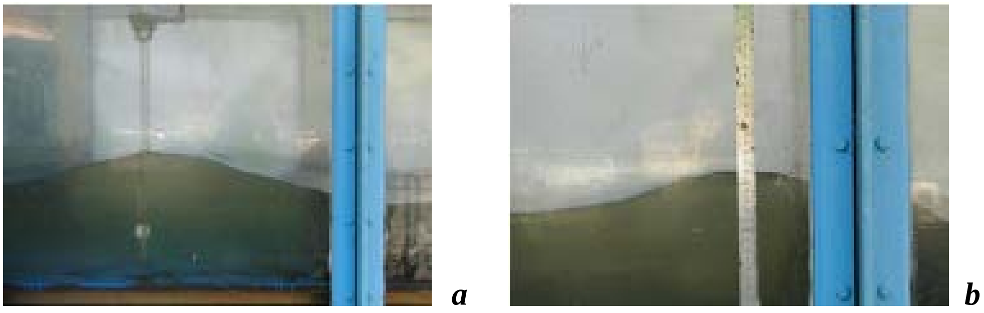

Fig. 1. Determination of wave heights on the model using capacitive wave recorders DUE (*a*) and a ruler (*b*)

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2) Kirkegaard, J., Wolters, G., Sutherland, J., Soulsby, R., Frostick, L., McLelland, S., Mercer, T. and Gerritsen, H., 2011. *Users Guide to Physical Modelling and Experimentation: Experience of the HYDRALAB Network*. London: CRC Press, 272 p. https://doi.org/10.1201/b11335

these conditions. In particular, if the same liquid is used on the model as in natural conditions, then it is impossible to simultaneously provide similarity in Froude (Fr) and Reynolds (Re) numbers. However, for a number of problems of great practical importance, similarity in both parameters is not required [3].

Thus, with the only wave motion or the impact of non-breaking waves on hydraulic structures, when the viscosity influence is small, the dynamic similarity of model and natural processes is determined by the equality of the Froude numbers. When studying waves on the surface of incompressible fluid, the Froude criterion can be written as follows

$$\mathrm{Fr} = \frac{h}{gT^2}, \tag{1}$$

where h – height of waves; g – gravitational acceleration; T – period of waves.

Limitations on wave parameters are conditioned upon the need to eliminate the noticeable influence of molecular viscosity and capillary effects. Capillarity (or surface tension) can be ignored if the wavelength on the model λ_m is greater than 20 cm [4]

$$\lambda_m > 20 \text{ cm}. \tag{2}$$

To neglect the internal dissipation of wave energy due to viscosity, condition [5] should be satisfied

$$\lambda_m > 400\sqrt{\upsilon \cdot T}, \tag{3}$$

where υ – kinematic viscosity of the fluid.

Another class of problems on the motion of a fluid with free surface includes cases when the friction in the fluid is significant, but the influence of molecular viscosity can be neglected. Examples of this kind are flows with highly developed turbulence at high Reynolds numbers. Such problems include problems on the interaction of waves with immersed barriers or permeable structures. The question of modeling of resistance forces or forces of hydrodynamic action in these cases can be reduced to the question of modeling of shape and mass of structural elements of constructions. Of course, it should be borne in mind that there is a lower limit on the size of the model, which is determined from the following conditions: the flow on the model must be turbulent and self-similar in terms of the Reynolds number [3]. When flowing around the bodies of various shapes, these requirements will be met if

$$\mathrm{Re} = \frac{V_m \cdot L_m}{\upsilon} \geq 500 \div 1000, \tag{4}$$

where V_m – characteristic speed on the model; L_m – characteristic size of an immersed body.

When liquid flows through holes in permeable screens (jets), self-similarity in the Reynolds number will take place if

$$\mathrm{Re} = \frac{V_m \cdot \delta_m}{\upsilon} \geq 100, \tag{5}$$

where δ_m – characteristic hole size.

The interaction of waves with a permeable dump becomes independent of the Reynolds number at

$$\mathrm{Re} = \frac{V_m \cdot D_m}{\upsilon} \geq 1000, \tag{6}$$

where D_m – dump element size.

Since the wave length is assumed to be more than 0.7 m in the hydraulic model in the wave basin, the influence of the surface tension and molecular viscosity of the liquid on the research results will be insignificant (see formulas (2)–(6)). Therefore, the conclusion is that the processes under study on the models will be dynamically similar to natural ones. To ensure the equality of the Froude numbers (1) on the model and in natural conditions, the scale of the wave period will be as follows

$$m_t = \frac{T_m}{T_n} = \sqrt{m_l},$$

where index *m* refers to the model, and index *n* refers to actual values.

The scale of the mass of structural elements of constructions is taken as follows

$$m_G = \frac{G_m}{G_n} = m_l^3.$$

When performing studies with pebble beaches, it was taken into account that the experiments should be carried out while observing the geometric similarity of the model and sediments to the natural part of the coast and the similarity of the model wave regime to the natural one. At the same time, the density of sediments of beach material on the model and in natural conditions should be the same, and the processes occurring in the inshore zone of pebble beaches are modeled reliably when using sediments with an average size of at least 0.5 mm in experiments [6].

Experimental studies were carried out in a wave flume with its length of 20 m, width of 0.6 m, and wall height of 1 m. Waves were generated by a shield wave generator installed in a pit near the end wall.

The experiments were carried out on a scale of 1:30. For the selected scale, a 7.3 m (219 m) plywood underwater coastal slope, simulating drying height in front of the coastal slope at low tide, was installed with a pitch of 0.005, which, under natural conditions, corresponded to the average value of the bottom slopes within the drying height area. Here and elsewhere in the text, the values corresponding to field data are given in brackets. The adjunction of the coastal slope test unit with the bottom of the flume is also made of plywood 2.44 m (73 m) long, installed with a pitch of 0.082 (Fig. 2). To maintain the roughness of the bottom, a layer of sand was applied to the plywood. The water depth in front of the beach scarp, equal to 12.0 cm (3.60 m), corresponded to the maximum sea level at high tide and remained unchanged in all experiments. With such a length of the shallow water area and depth near the beach scarp, the height of the waves acting on the beach made 5.3 cm (1.60 m). The average period for waves of this height made 1.1 s (6.0 s) [7]. Constant change in the water level in the flume, simulating the phases of high tide and low tide, taking into account the time of their action

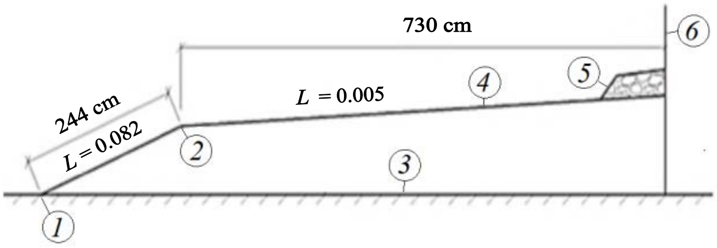


Fig. 2. Scheme of the model during wave flume studies of the profile dynamics of a pebble beach at tide: *1* – adjunction of the drying height with the test unit bottom; *2* – knee of the bottom profile; *3* – test unit bottom; *4* – drying height bottom; *5* – pebble beach under study; *6* – beach scarp

(according to the scale factor of time) and amplitude (tide height), was selected by opening and closing the water inlet and outlet valves.

Experiments were performed for two sizes of beach-forming material with median diameters $d_{50\%}$ = 0.74 mm (22.2 mm) and $d_{50\%}$ = 1.19 mm (35.7 mm). For these sediment sizes under the selected wave mode in natural conditions, profiles of relative dynamic equilibrium were calculated, according to which, taking into account the compaction of sediments during wave processing, the construction profiles of the initial backfill were determined (Fig. 3). Based on the geometric scale, the construction profile of the original backfill was reproduced on the model and remained unchanged for the corresponding size of the beach-forming material during the experiments (Fig. 4).

Results of studies and their discussion

In the first series of experiments, studies in a wave flume were carried out with a beach-forming material with a particle size of $d_{50\%}$ = 0.74 mm (22.2 mm). First, with the water level unchanged during the experiment and corresponding to its maximum mark during the high tide phase, the profile of a pebble beach was formed under the influence of waves on the initial backfill of beach-forming material near the beach scarp (Fig. 5, Profile *2*). The profiles formed during tidal cycles were compared with this profile in further studies.

In the course of the experiment, at a constant water level in the flume, under the influence of waves breaking on the initial backfill of the beach-forming material, a shift of sediments to the breakdown area was observed with the formation of a beach profile with a steep underwater part, which is typical for natural pebble beaches [8]. At the end of the experiment, the surface beach was 24.0 cm (7.2 m) wide, and there was no storm bar in its upper part.

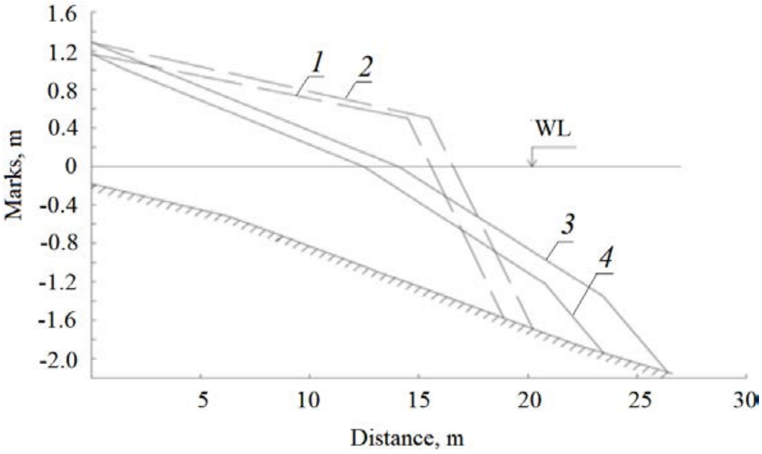
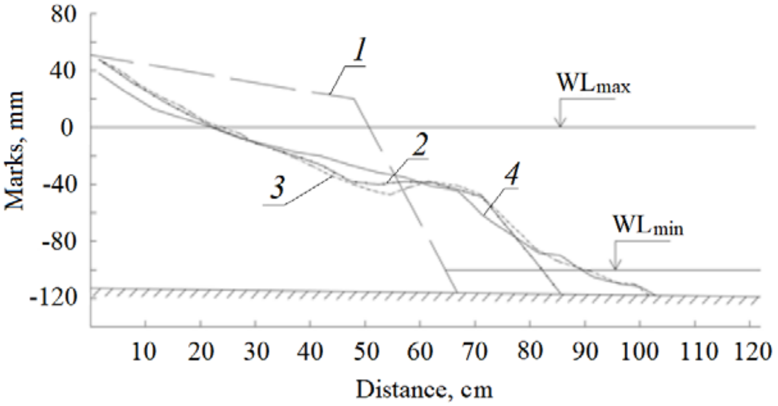


Fig. 3. Calculated profiles of the relative dynamic equilibrium of wave-absorbing pebble beaches and construction profiles of the initial backfilling of beach-forming material: *1* – construction profile for $d_{50\%}$ = 0.022 м; *2* – construction profile for $d_{50\%}$ = 0.036 м; *3* – relative dynamic equilibrium profile for $d_{50\%}$ = 0.022 м; *4* – relative dynamic equilibrium profile for $d_{50\%}$ = 0.036 м. WL – water level

Fig. 4. Model of the initial backfill of the beach-forming material. The horizontal line shows the water level at high tide



F i g . 5 . Deformation of the beach profile, composed of sediments with a size of $d_{50\%}$ = 0.74 mm, worked out at the constant maximum level during the tidal cycle; *1* – profile of the initial backfill; *2* – profile developed at the constant maximum water level; *3* – profile developed during the low tide phase; *4* – profile developed during the high tide phase

In the next experiment, with a continuous decrease in the water level in a flume simulating the low tide phase, under the influence of waves on the profile formed at the maximum water level, the beach material was displaced down the slope seaward of the bottom of the beach worked out at the maximum level. As a result of this displacement, a more gentle profile of the underwater part of the pebble beach was formed. At the same time, an insignificant part of the sediments was moved to the upper part of the profile, where an increase in the beach marks was recorded. The total protrusion of the underwater beach boundary relative to the profile developed at the constant maximum water level made 16.1 cm (4.83 m). In contrast to the previous experiment, when the water level decreased (low tide phase), swells were formed in the underwater part of the beach. With continuous decrease in the water level, the upper part of the profile developed at the constant maximum level changed little (Fig. 5, Profile *3*).

In the subsequent experiment reconstructing the conditions of the high tide, when the waves act on the profile worked out at low tide (Fig. 5, Profile *3*), no erosion of its underwater part protruded at low tide and displacement of the underwater boundary of the beach towards the shore were observed (Fig. 5, Profile *4*). Beach material that was pushed down at low tide was not placed back at high tide. During the experiment, under conditions of the increase of water levels, the formation of above-water swells at intermediate water levels was observed, which were washed away with further increase in the level. At the end of the experiment, with the increase in the water level (at high tide), an increase in the profile marks of the pebble beach was recorded seaward of the shore (Fig. 5, Profile *4*). At the same time, there was a decrease in the elevations of the surface part of the beach formed during the simulation of low tide, due to the displacement of sediments into the underwater part of the profile. The processes occurring on the pebble beach at high tide led to some smoothing of the beach profile.

During one tidal cycle, the width of the surface part of the beach, worked out at the constant maximum level, changed insignificantly: 22.4 cm (6.7 m) at the constant maximum level, 24.0 cm (7.2 m) at low tide, and 22.0 cm (6.6 m) at high tide. At low tide, the underwater boundary, compared to the pebble beach worked out at the maximum level unchanged during the experiment, moved out into the sea by 16.1 cm (4.83 m).

As follows from the experiments, the tidal factor affects the formation of the profile of a pebble beach, as a result of which it differs from the profile developed by waves in the initial backfill of beach-forming material at the constant maximum level. At low tide, the surface part of the beach is washed out and the beach material is displaced into its underwater part, which leads to the protrusion of the underwater beach boundary towards the sea. At high tide, material that was displaced at low tide does not return to the top of the profile. The underwater part of the beach profile formed during the tidal cycle turned out to be flatter than the profile at the constant maximum water level. The height of the upper surface part of the beach, developed at high tide, turned out to be less than on the profile at low tide.

In general, further experiments concerning the impact of waves directly on the initial backfill of beach-forming material with $d_{50\%}$ = 0.74 mm at different combinations of high and low tide phases proved the results obtained above on the description of their impact on the formation of a beach profile composed of large rock fragments.

Under the influence of waves on the initial backfill of the beach-forming material, in combination with a continuous water level rise (high tide), the beach material shifted towards the sea, as a result of which the underwater boundary of the formed beach moved forward compared to the position of the original backfill by 19.5 cm (5.85 m). The beach profile developed by the action of waves on the initial backfill of beach-forming material at high tide (Fig. 6, Profile *2*) differed little from the profile obtained at the constant maximum level (Fig. 5, Profile *2*).

Under the influence of waves at low tide on the profile of the beach formed from the material of the initial backfill at high tide (Fig. 6, Profile *2*), as in previous experiments, the bottom (underwater boundary) of the pebble beach moved forward by 12.0 cm (3.6 m) (Fig. 6, Profile *3*), while the width of the surface part of the beach decreased from 25.5 (7.65 m) to 24.0 cm (7.20 m). These results are close to the previously obtained data.

Fig. 7 shows the beach profiles formed as a result of repeated wave impact on the initial backfill of the beach-forming material. Figure 8 shows the averaged profiles

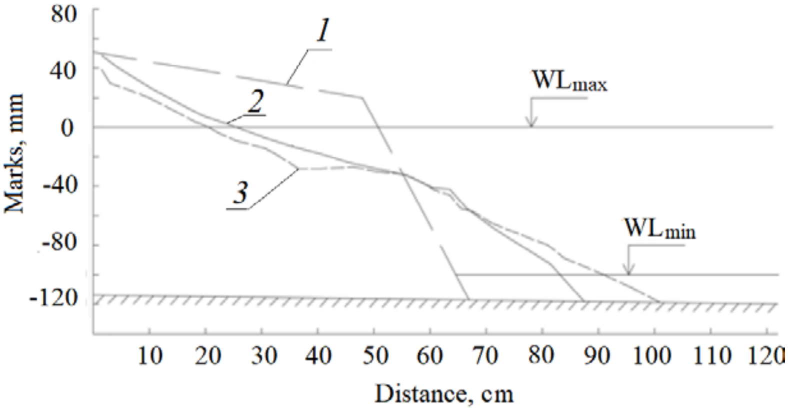


Fig. 6. Beach profiles formed during the high tide phase under the action of waves on the initial backfill of beach-forming material with a particle size of $d_{50\%}$ = 0.74 mm (22.2 mm): *1* – profile of the initial backfill; *2* – beach profile developed in the initial backfill of beach-forming material during the high tide phase; *3* – beach profile formed in the low tide phase under the influence of waves on the profile developed at high tide

generated by waves at low tide when they act on a profile formed from the material of the original backfill at high tide (Fig. 6, Profile *2*) and when they act on the original backfill (construction profile) (Fig. 7) of the beach-forming material with a particle size of $d_{50\%}$ = 0.74 mm (22.2 mm). As follows from the results obtained, the warping-off of large rock beach material under different initial conditions of the experiments took place to the same depth.

The second series of experiments were devoted to the influence of the tidal cycle on the formation of the profile of a wave-absorbing pebble beach composed of sediments with a particle size of $d_{50\%}$ = 1.19 mm (35.7 mm). The wave parameters remained the same as in the previous series of experiments with the beach-forming material with a particle size of $d_{50\%}$ = 0.74 mm (22.2 mm): wave height – 5.3 cm (1.60 m), period – 1.1 s (6.0 s). Beach profiles worked out by waves in combination with tidal level fluctuations were compared with the profile formed when waves acted on the initial backfill of beach-forming material with a particle size of $d_{50\%}$ = 1.19 mm (35.7 mm) (see Fig. 3) at the constant maximum water level in the high tide phase (Fig. 9). This profile is shown in Fig. 10 (Profile *2*).

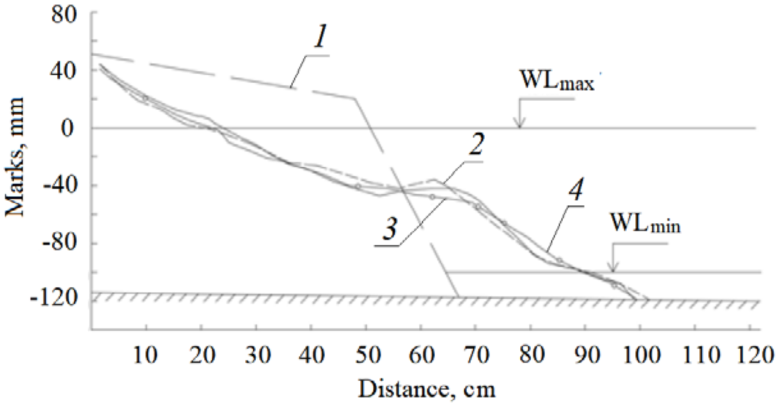


Fig. 7. Beach profiles formed in the low tide phase under the action of waves on the initial filling of material with a particle size of $d_{50\%}$ = 0.74 mm (22.2 mm): *1* – profile of the initial backfill; *2–4* – beach profiles formed in the low tide phase under the influence of waves on the initial backfill of material with a particle size of $d_{50\%}$ = 0.74 mm (22.2 mm)

With the water level in the flume unchanged during the experiment, under the influence of waves, the breakdown of which occurred on the underwater continuation of the initial backfill of the beach-forming material, the model showed a displacement of the beach material from its surface to the underwater part. In the zone of wave breaking, a beach profile with a steep slope was formed. In contrast to the beach, which was composed of finer material (see Fig. 5), its surface part ended in a storm bar. The bottom of the formed beach moved out into the sea by 11.7 cm (3.51 m) compared to the underwater boundary of the original backfill. In the previous series of experiments with finer beach-forming material, this protrusion made 16.1 cm (5.43 m). The width of the surface part of the beach, composed of coarser material, made 23.6 cm (7.05 m), which exceeded the similar width for sediments of smaller size (22.4 cm). This does not contradict the general ideas concerning the influence of beach material size on the formation of the profile of a pebble beach and indicates the correct reflection of the processes occurring in the coastal zone on the model.

Further experiments, as previous series, aimed at the study of reconfiguration of the beach profile composed of sediments with a particle size of $d_{50\%}$ = 1.19 mm (35.7 mm) and worked out by the initial wave at the constant water level with successive alteration of low tide and high tide phases.

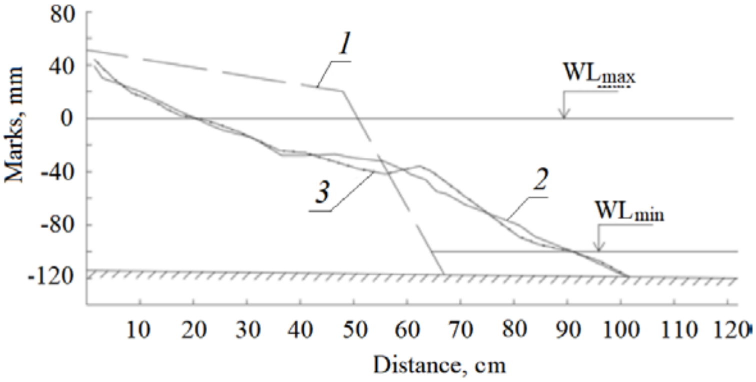


Fig. 8. Beach profiles worked out in the low tide phase under the influence of waves on the profile formed at high tide and under their influence on the initial backfilling of the beach-forming material with a particle size of $d_{50\%}$ = 0.74 mm (22.2mm): *1* – profile of the initial backfill; *2* – profile developed at low tide when the waves act on the profile formed at high tide; *3* – profile formed at low tide under the influence of waves on the initial backfill of beach-forming material

At low tide, as in the case of finer beach material, there was a reconstruction of the profile formed at the constant maximum water level, and the warping-off of sediments to a depth. The bottom of the pebble beach at low tide under the influence of waves moved out into the sea by 13.5 cm (4.05 m) compared with the initial profile. At the same time, the width of the surface part of the beach increased by 6.0 cm (1.80 m) as a result of sediment movement not only downward, but also upward along the profile. An increase in the width of the surface part of the beach was noted with finer material also. As can be seen from Fig. 10 (Profile *3*), at low tide, a series of accumulation swells formed on the surface of the underwater part of the beach, but not as pronounced as with smaller sediments. The same swells, in contrast to the beach composed of smaller sediments, were also formed in the surface part of the beach.

In the next experiment, the conditions of the high tide are reconstructed, as a result of which, under the influence of waves on the profile developed at low tide, erosion of the surface part of the beach was observed with a decrease in its height and accumulation of sediments with the formation of an underwater swell in the wave breaking area. At the same time, as can be seen from Fig. 10 (Profile *4*), the position of the underwater boundary of the pebble beach, worked out by the waves at low tide, remained unchanged.

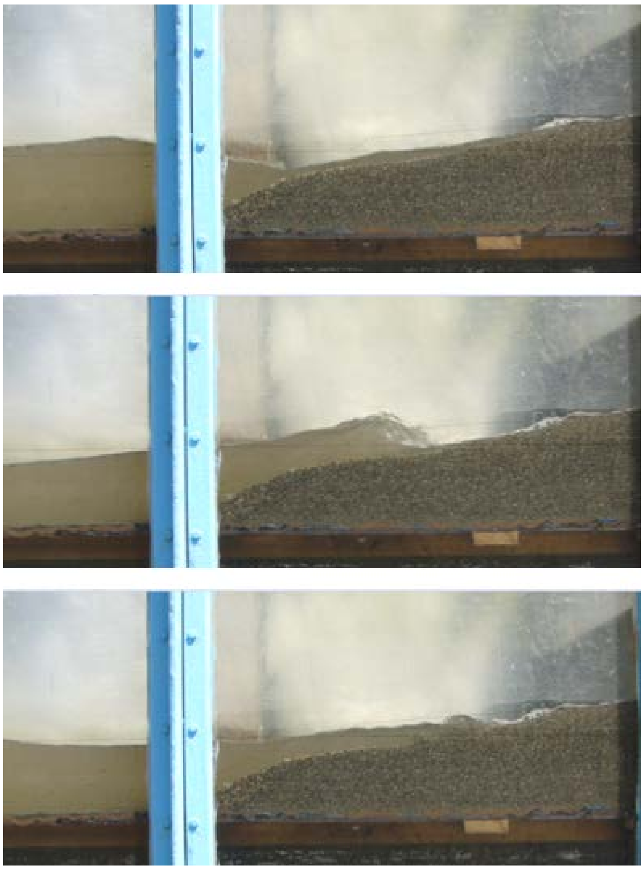


Fig. 9. Impact of waves on the initial backfill of beach-forming material with a size of $d_{50\%}$ = 1.19 mm (35.7 mm) at the constant maximum level

Comparison of data on the formation of profiles of pebble beaches, composed of sediments with a particle size of $d_{50\%}$ = 0.74 mm (22.2 mm) and $d_{50\%}$ = 1.19 mm (35.6 mm), indicates that at low tide the beach material, regardless of its size, shifts towards the sea compared to a profile generated at the constant maximum water level. For fine material, this displacement made 16.2 cm (4.86 m), and for coarse material, it was 14.3 cm (4.29 m), due to the greater mobility of fine material. Comparison of the beach profiles presented in Fig. 5 and Fig. 10 shows that with coarse beach material a steeper underwater part of the profile is formed at low tide. In the middle underwater part of the profile, with coarse material, in contrast to fine material, during high tide, due to erosion of the surface part of the beach, accumulation forms are formed, which leads to the formation of a profile of a complex shape at low tide. With fine material at high tide, beach profile smoothing is noted.

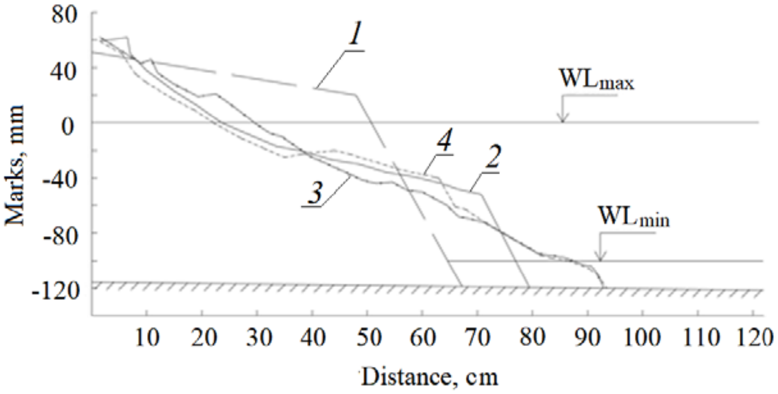


Fig. 10. Deformation of the beach profile composed of sediments with a size of $d_{50\%}$ = 1.19 mm (35.7 mm), worked out at the constant maximum level during the tidal cycle. *1* – profile of the initial backfill; *2* – profile developed at the constant maximum water level; *3* – profile developed during the ebb phase when waves act on the profile formed at the constant maximum water level; *4* – profile developed during the high tide phase, when the waves act on the profile formed at low tide

Apparently, this is explained by the coarseness of the beach-forming material, when, under the same wave conditions, the moving effect for large sediments decreases compared with small ones.

In further experiments, as with finer material, beach profiles were formed with waves acting directly on the initial backfill of beach-forming material with $d_{50\%}$ = 1.19 mm (35.7 mm), with different combinations of high and low tide phases. The experiments carried out confirmed the data obtained earlier with fine material on the influence of the alternation of tidal phases on the formation of the profile of a wave-absorbing pebble beach composed of large rock fragments.

Conclusion

On the basis of experiments performed in a wave tray, a difference was revealed in the profiles of pebble beaches formed on tideless and tidal seas under the influence of waves. On tidal seas, in comparison with tideless seas, during the formation of the profile of a wave-absorbing pebble beach at low tide, the beach-forming material is pulled to depths greater than in tideless ones. At high tide, this material does not fully return to the upper part of the profile of the wave-absorbing pebble beach. The irretrievable displacement during low tide of a part of the volume of the beach-forming material beyond the calculated profile of relative dynamic equilibrium, calculated for the conditions of tideless seas, leads to a decrease in the width of the wave-absorbing pebble beach and a decrease in its wave-damping properties. When creating wave-absorbing pebble beaches on tidal seas and calculating the initial backfill of beach-forming material, it is necessary to take into account the volume of irretrievable displacement of large rock sediments to the lower part of the formed profile during low tide.

According to the studies, the volume of beach-forming material that is displaced at low tide to a depth and not returned back at high tide makes about 5 %.

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Nestifor A. Yaroslavtsev – development of the modeling technique, conducting experiments in a wave flume, analysis of the results obtained, preparation of the text of the article and list of references

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