ISSN 0001-4370, Oceanology, 2020, Vol. 60, No. 3, pp. 412–420. © Pleiades Publishing, Inc., 2020.
Russian Text © The Author(s), 2020, published in Okeanologiya, 2020, Vol. 60, No. 3, pp. 474–484.

MARINE GEOLOGY

The Effect of a Groin Field on a Sandy Beach

I. O. Leont'yev[a, *] **and T. M. Akivis**[a, **]
[a]*Shirshov Institute of Oceanology Russian Academy of Sciences, Moscow, Russia*
**e-mail: igor.leontiev@gmail.com*
***e-mail: akivis@yandex.ru*

Received March 25, 2019; revised June 24, 2019; accepted December 16, 2019

Abstract—A model has been developed that explains sediment accumulation within a groin field from the aspect of mass conservation. The model revealed that intergroin sedimentation is related to the gradient of the adjacent longshore sediment transport. An important model parameter is the length Λ of the structure's zone of influence. It is shown that the accumulation rate reaches its maximum when the intergroin distance is close to Λ, while material accretion terminates when the distance is close to 2Λ. The optimal relationships between the intergroin distance, groin length, and width of the sediment flux have been obtained. This allows operational forecasting of the accumulation volume and distance the beach advances within time periods from hours to decades. The model can calculating the optimal groin field parameters to achieve the required performance and avoid unnecessary impacts. The calculations reasonably agreement with published observations.

Keywords: groin field, sandy beach, alongshore sediment transport, accretion, downdrift erosion

DOI: 10.1134/S0001437020030042

INTRODUCTION

A groin field is a series of linear structures adjacent to the shore, offset from each other by a certain distance. The use of groins to protect coasts has a long history, described, e.g., in [7]. However, there is still no established opinion on the feasibility of using such structures in particular conditions. Some experts focus on the negative impact of groins on adjacent coastal areas where downdrift erosion occurs. Nevertheless, structures of this type continue to be built, and there are many examples of their successful operation in expanding beaches and protecting coasts [6, 7, 11, 14–16]. The accumulated experience clearly indicates that it makes sense to use groins only if sufficient alongshore sediment transport is generated by waves and accompanying currents.

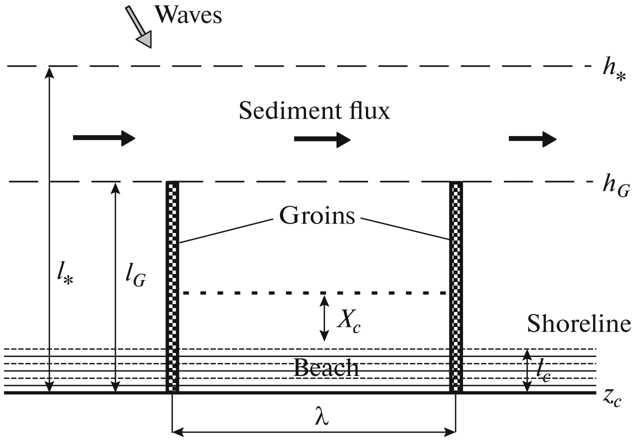

Fig. 1. Diagram of shore and groin field. l_*, width of sediment flux (active region of profile); h_*, closure depth; l_G, groin length; h_G, depth at head of groin; l_c and z_c, width and elevation of beach; λ, distance between groins or step of field; X_c, advancement of shoreline as result of groins.

The expected effect of groins is that they intercept part of the alongshore flux and the material trapped between groins feeds beach growth (Fig. 1). Although the idea is quite simple, its implementation in practice does not always yield the desired results. Consequences depend on both regional conditions and the parameters of structures, including their length and step.

Groin planning for beach preservation raises a number of questions, e.g., how to estimate the annual accumulative volume for the given groin parameters, or how long and how far apart should the structures be to ensure the optimal beach width increase rate? Attempts to answer these questions are based mainly on empirical arguments [8, 11].

In recent decades, numerical morphodynamics models have also been used for calculations [12, 13], which can reproduce in detail various scenarios of wave impacts for coastal structures, but they are also time-intensive in terms of data preparation and calculations. Such models are expedient when a choice has already been made in favor of a particular project. However, at the preliminary stage, when it is necessary to estimate and compare different project options,

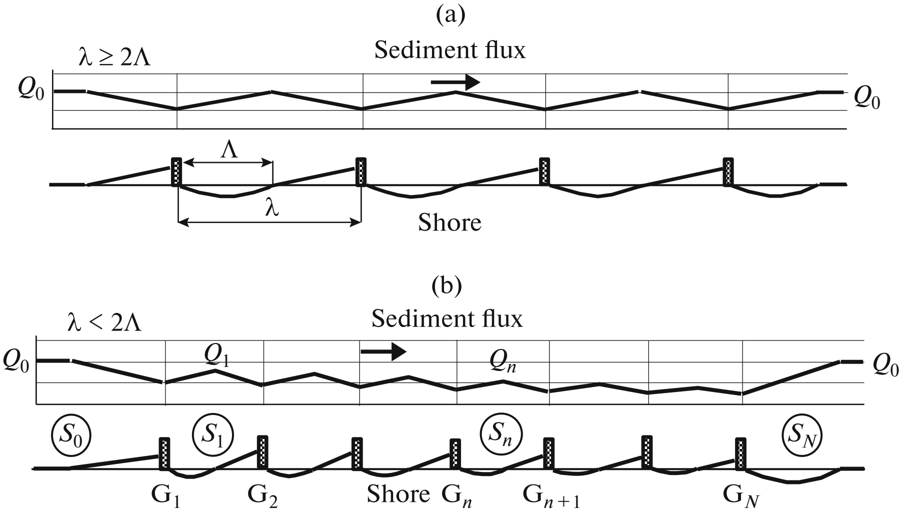

Fig. 2. Changes in sediment flux and shore contour at relatively large (a) and relatively small (b) intergroin distances λ. Scale is represented by extent of zone of influence of structure Λ.

simpler models that reflect the essence of processes in less detail but significantly reduce the time to obtain the necessary information, can be useful.

One such model is presented in this paper. The accumulative effect of the groin field is explained from the aspect of the law of mass conservation. The results illustrate how a groin field works under particular conditions and what consequences can arise due to altering its parameters. The obtained dependences permit an operational forecast of accumulative volume and the distance that a beach can advance over a certain time period. Recommendations on selecting the optimal field parameters are also discussed. Published data are used to verify the model.

CONCEPT OF THE MODEL

The starting point is the traditional assumption that changes in the shore contour are mainly associated with changes in the alongshore sediment flux created by the waves, and the bottom profile is close to equilibrium and can move behind the contour without appreciable changes in shape.

We consider the most typical situation, when the groin length l_G is less than the width of the alongshore sediment flux l_* and some of the material can pass around the outside of the structures (Fig. 1). We also introduce a postulate according to which the influence of barriers on the sediment flux is limited to a certain distance Λ, both on the updrift and downdrift sides of the structure (Fig. 2).

If the step of the field λ is sufficiently large and satisfies the condition $\lambda \geq 2\Lambda$, then individual groins barely affect each other and can be considered independent barriers for longshore sediment flux (Fig. 2a). In front of the obstacle, the flux is unloaded; downstream, it is saturated and restored to its initial value Q_0. Accumulation from the updrift side of the obstacle causes the beach to advance, whereas a deficit of material from the downdrift side causes the shore to recede. For all subsequent elements of the groin field, the pattern is repeated. The shoreline acquires an undulate pattern, but its average position does not change, since accumulation and erosion generally cancel each other out (Fig. 2a).

Below, we demonstrate that a groin field is able to accumulate material only when its step λ is less than 2Λ (Fig. 2b). Suppose that in an area located upstream, acting waves create alongshore sediment discharge Q_0. The first groin (G_1) traps part of it b_1Q_0, and at its location the discharge decreases to $Q_0 - b_1Q_0$. Quantity b_1Q_0 is clearly equivalent to the accumulation rate Ac_0 in the area in front of the first groin: $Ac_0 = b_1Q_0$.

Downstream, the discharge increases with distance from the obstacle, and if the distance λ_1 to the next groin is 2Λ, the increase will be b_1Q_0 and the flux will be restored to its initial value Q_0 (Fig. 2a). However, for smaller λ_1, the increase may only be partial $K_1b_1Q_0$, where $K_1 < 1$ and, obviously, depends on λ_1. Thus, maximum sediment discharge Q_1 for the first intergroin space S_1 should be equal to

$$Q_1 = Q_0 - b_1Q_0 + K_1b_1Q_0 = [1 - (1 - K_1)b_1]Q_0.$$

In the flux restoration area on the downdrift side of the first groin G_1 (Fig. 2b), erosion will occur at a rate of $K_1b_1Q_0$. At the same time, in the flux unloading zone on the updrift side of the second groin (G_2), sediment will accumulate at a rate of b_2Q_1. Therefore, the resulting accumulation in the first intergroin space S_1 is defined as

$$Ac_1 = b_2 Q_1 - K_1 b_1 Q_0 \\ = \left[b_2(1-b_1) - b_1(1-b_2)K_1\right] Q_0.$$

In a similar way, we find the accumulation rate in the next space (S_2):

$$Q_2 = \left[1 - (1-K_2)b_2\right] Q_1, \\ Ac_2 = \left[b_3(1-b_2) - b_2(1-b_3)K_2\right] Q_1,$$

as a result, we arrive at relations that determine sediment discharge and accumulation in each *n*th intergroin space (S_n):

$$Q_n = \left[1 - (1-K_n)b_n\right] Q_{n-1}, \tag{1}$$

$$Ac_n = \left[b_{n+1}(1-b_n) - b_n(1-b_{n+1})K_n\right] Q_{n-1}, \\ n = 1, 2, 3, \ldots, N-1, \tag{2}$$

where N is the number of groins in the field (the number of intergroin spaces is $N - 1$). Obviously, sediment transport decreases downstream; accumulation is maximum in the first intergroin space and decreases in the successive groin compartments (Fig. 2b).

The last groin in the field (with number N) traps part of the sediment discharge $b_N Q_{N-1}$, and at its location, $Q_{N-1} - b_N Q_{N-1} = (1-b_N)Q_{N-1}$. Downstream, discharge is gradually restored to its initial value Q_0 (Fig. 2b). The difference in discharges is equivalent to the downdrift erosion rate Er_N:

$$Er_N = Q_0 - (1-b_N)Q_{N-1}. \tag{3}$$

We considered the situation when the sediment flux occurs from left to right when viewed from the beach (Figs. 1 and 2). When waves approach on the right of the normal to the beach, the flux direction changes to the opposite and its initial value Q_N has the same sense as Q_0. In the area to the right of groin number N, material now accumulates at a rate of Ac_N, and downdrift erosion at a rate of Er_0 is recorded below the first groin. It is easy to check that this situation can be described by the same relations (1)–(3) with a certain modification.

Representing the found dependences for the accumulation (Ac) and erosion (Er) rates as a function of sediment transport at the entrance to the groin field (Q_0 and Q_N), we arrive at the relations

$$Ac_0 = b_1 Q_0, \quad Ac_N = b_N Q_N. \tag{4}$$

$$Ac_n = a_n \prod_1^n c_n Q_0, \quad Ac'_n = a'_n \prod_1^{N-n} c'_n Q_N, \\ n = 1, 2, 3, \ldots, N-1, \tag{5}$$

$$a_n = b_{n+1}(1-b_n) - b_n(1-b_{n+1})K_n, \\ c_n = 1 - (1-K_n)b_n, \tag{6}$$

$$a'_n = b_n(1-b_{n+1}) - b_{n+1}(1-b_n)K_n, \\ c'_n = 1 - (1-K_n)b_{n+1}, \tag{7}$$

$$Er_N = \left[1 - (1-b_N)\prod_1^{N-1} c_n\right] Q_0, \\ Er_0 = \left[1 - (1-b_1)\prod_1^{N-1} c'_n\right] Q_N, \tag{8}$$

where the values with primes correspond to sediment flux from right to left.

In the particular case when each groin in the field is characterized by the same value $b = \text{const}$ and the intergroin distance is constant ($\lambda = \text{const}$, $K = \text{const}$), the above dependences are simplified:

$$Ac_0 = bQ_0, \quad Ac_N = bQ_N, \tag{9}$$

$$Ac_n = ac^n Q_0, \quad Ac'_n = ac^{N-n} Q_N, \\ n = 1, 2, 3, \ldots, N-1, \tag{10}$$

$$a = b(1-b)(1-K), \quad c = 1 - (1-K)b, \tag{11}$$

$$Er_N = \left[1 - (1-b)c^{N-1}\right] Q_0, \\ Er_0 = \left[1 - (1-b)c^{N-1}\right] Q_N. \tag{12}$$

MODEL PARAMETERS

Let us determine the model parameters b, K, Λ, Q_0, and h_*. Quantity b, which represents the fraction of sediment transport trapped by the groin, depends on the depth ratio at its end h_G and on the boundary of the longshore sediment flux h_* (Fig. 1); with allowance for the permeability of the structure ε_P, it is estimated as [5, 12]

$$b = (1-\varepsilon_p)(h_G/h_*), \quad h_G/h_* \le 1 \tag{13}$$

(for a solid structure, $\varepsilon_P = 0$). The constancy of b_n assumed in (9)–(12) is possible under conditions of a homogeneous beach with the same groin design and length.

Quantity K, which reflects degree of restoration of sediment flux should increase with increasing intergroin distance λ and reach a maximum of $K = 1$ for $\lambda/2\Lambda = 1$. Based on this, we can take

$$K = \lambda/2\Lambda. \tag{14}$$

The length of the zone of influence of the structure Λ, according to the results of [5], can be estimated as

$$\Lambda = (l_G/l_*)^{0.5} l_*, \tag{15}$$

where l_G is groin length and l_* is the length of the active part of the profile, limited to a depth of h_* and the rising of the beach z_c (Fig. 1).

Alongshore sediment discharge at the entrance to the groin field Q_0 (or its equivalent Q_N) determines the scale of morphological changes and should be estimated with sufficient reliability. In this case, the following well-proven formula is used [3, 4]:

$$Q_0 = 0.005\mu_h\left(0.8 + 0.02\frac{\sqrt{gh_B}}{w_g}\right) \times H_B^2\sqrt{gh_B}\sin\Theta_B\cos\Theta_B, \qquad (16)$$

where transport is expressed in m^3/h, $\mu_h = 3600 \times \left[(\rho_g/\rho - 1)(1-\sigma)\right]^{-1}$, ρ_g/ρ is the ratio of the density of solid particles to the density of water, σ is the porosity of sandy sediments, g is gravitational acceleration, w_g is the settling velocity of solid particles, and h_B is the breaking depth of waves 1% cumulative exceedance (with a height of $H_{1\%\infty}$),

$$h_B = \left(\frac{1}{4\pi\gamma_B^2}\right)^{0.4} H_{1\%\infty}^{0.8}\left(gT^2\right)^{0.2}\left(\frac{\cos\Theta_\infty}{\cos\Theta_B}\right)^{0.4}, \qquad (17)$$

subscripts “∞”and "B” refer to deep water and to the breaking point, respectively, $\gamma_B = 0.8$, and T is the period of the wave spectrum peak. Quantity H_B in (16) entails the mean-square height at the breaking point, which, taking into account the Rayleigh distribution of wave heights, is $H_B = 0.37h_B$. The wave incidence angle at breaking point Θ_B (between the wave ray and the normal to the shore) is calculated according to the law of refraction, $\sin\Theta/C = \text{const}$ where C is the wave propagation velocity. Alongshore sediment transport can also be estimated by the version of the well-known CERC formula given in [4].

The closure depth h_* for a single wave impact is equivalent to the wave breaking depth h_B determined in (17) [1]. On an annual or interannual scale, quantity h_* is determined by the height of the storm waves H_{s12h} active at least 12 h/year [10]:

$$h_* = 2.8H_{s12h}^{2/3}. \qquad (18)$$

OPTIMAL RELATIONS OF THE GROIN PARAMETERS

The efficiency of groins as an accumulative mechanism, according to formulas (10)–(11), is directly proportional to $a = b(1-b)(1-K)$. The product of $b(1-b)$ reaches a maximum at $b = 0.5$, which means that the accumulation rate in the intergroin space is maximum when the groin traps half material transported along the beach. For this, according to (13), it is required that the groin go to a depth corresponding to half the closure depth (i.e., an impermeable structure).

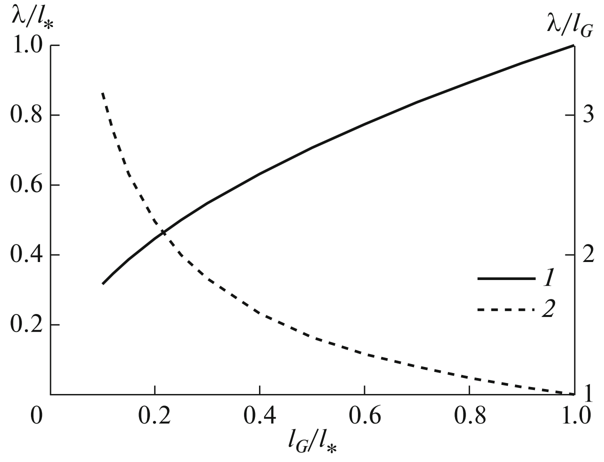

Fig. 3. Optimal intergroin distance as function of their relative length l_G/l_*: *1*, ratio of distance to length of active profile, λ/l_*; *2*, ratio of distance to length of groin, λ/l_G.

The accumulative capacity of the groin should increase with decreasing K, i.e., with a decrease in the relative offset between groins (see formula (14)). However, if the distance between groins is too small, due to inertia, the sediment flux simply will not have time to react to them. The previously introduced length of the zone of influence of a structure Λ in essence characterizes the distance at which the sediment flux can be restored under the action of external factors. Therefore, the minimum intergroin distance λ should be no less than Λ, and the maximum, as mentioned above, should be no greater than 2Λ:

$$\Lambda \le \lambda < 2\Lambda \quad \text{or} \quad 0.5 \le K < 1. \qquad (19)$$

This range of values K limits the possible step of the groin field and also determines the area of applicability of our model.

Obviously, for $\lambda = \Lambda$ or $K = 0.5$, the accumulation is maximum. According to (15), the following dependences between the offset of the groin field λ and their length l_G correspond to the given condition:

$$\lambda/l_* = \left(l_G/l_*\right)^{0.5} \quad \text{or} \quad \lambda/l_G = \left(l_G/l_*\right)^{-0.5}. \qquad (20)$$

Dependences (20) are plotted in Fig. 3.

The distance between groins should also increase in proportion to $\sqrt{l_G}$. For short groins, $l_G/l_* = 0.1$, the optimal offset of the field is close to $3l_G$, whereas for long structures, $l_G/l_* = 0.5$, the distance λ should only be around 1.4 l_G. In this regard, we note that the values of λ/l_G used in practice are usually in the range from 1 to 3 [7, 11].

ANNUAL VOLUME OF ACCUMULATION AND DISPLACEMENT OF THE SHORELINE

Under the action of waves with given parameters over time Δt the accumulation volume in the nth intergroin space will be $V_n = Ac_n\Delta t$. To estimate the annual accumulation volume Ω_n, it is necessary to add up the elementary volumes V_n calculated for different gradations of wave directions (j) and heights (i) taking into account their duration throughout the year t_{wi}. In this case, it is necessary to separate the directions to the left (j_L) and right (j_R) of the normal to the beach and calculate the corresponding volumes $\Omega_n^{(L)} = \sum_{j_L}\left(\sum_i Ac_{ni}t_{wi}\right)_{j_L}$ and $\Omega_n^{(R)} = \sum_{j_R}\left(\sum_i Ac'_n t_{wi}\right)_{j_R}$. Taking into account relations (5), we obtain

$$\Omega_n = \Omega_n^{(L)} + \Omega_n^{(R)} = a_n\prod_1^n c_n Q_{0\Sigma} + a'_n\prod_1^{N-n} c'_n Q_{N\Sigma}, \quad (21)$$

$$Q_{0\Sigma} = \sum_{jL}\left(\sum_i Q_{0i}t_{wi}\right)_{jL}, \quad Q_{N\Sigma} = \sum_{jR}\left(\sum_i Q_{Ni}t_{wi}\right)_{jR}, \quad (22)$$

where $Q_{0\Sigma}$ and $Q_{N\Sigma}$ are the annual sediment fluxes transported, respectively, to the left and right boundaries of the groin field (m^3/year).

The accumulation of material will cause the beach and its entire active profile to advance by an average distance of Δx_n. In accordance with the condition of mass conservation and the adopted assumption that the properties of the active profile are retained, we have the equality $\Omega_n = \left(h_* + z_c\right)\lambda_n\Delta x_n$, whence the average annual expansion of the beach is determined as

$$\Delta x_n = \frac{\Omega_n}{(h_* + z_c)\lambda_n}. \quad (23)$$

In adjacent areas to the left and right of the groin field (S_0 and S_N, Fig. 2b), the annual sediment balance is determined by the difference between the total accumulation and downdrift erosion: $\Omega_0 = \sum_{j_L}\left(\sum_i Ac_{0i}t_{wi}\right)_{j_L} - \sum_{jR}\left(\sum_i Er_{0i}t_{wi}\right)_{jR}$ and $\Omega_N = \sum_{j_R}\left(\sum_i Ac_{Ni}t_{wi}\right)_{j_R} - \sum_{jL}\left(\sum_i Er_{Ni}t_{wi}\right)_{jL}$. Taking into account (4) and (8), the resulting volumes Ω_0 and Ω_N are expressed as

$$\Omega_0 = b_1 Q_{0\Sigma} - \left[1 - \left(1 - b_1\right)\prod_1^{N-1} c'_n\right] Q_{N\Sigma}, \quad (24)$$

$$\Omega_N = b_N Q_{N\Sigma} - [1 - \left(1 - b_N\right)\prod_1^{N-1} c_n] Q_{0\Sigma}. \quad (25)$$

The average annual shoreline displacements beyond the margins of the groin field Δx_0 and Δx_N are determined by analogy with (23) as

$$\Delta x_0 = \frac{\Omega_0}{\left(h_* + z_c\right)L}, \quad \Delta x_N = \frac{\Omega_N}{\left(h_* + z_c\right)L}, \quad (26)$$

where L is the length of the perturbation zones. The influence of the groin field on adjacent areas of the beach is similar to that of a single obstacle of corresponding size, for which the length L of the perturbation zones increases over time in accordance with the dependence [5]

$$L = \Lambda\sqrt{t_Y}, \quad (27)$$

where Λ is determined from (15) and t_Y is the number of years elapsed since the structure was built. Clearly, quantities Δx_0 and Δx_N can be both positive (the beach advances) and negative (the beach recedes).

SHORT-TERM FORECAST

For relatively short time intervals, the annual accumulative volume Ω_n and beach growth Δx_n are approximately constant [15], and the total beach width X_{cn} is directly proportional to the number of years elapsed t_Y: $X_{cn} = t_Y\Delta x_n$. However, as the beach advances, accumulation should slow due to the decreasing trapping capacity of the groins. In other words, for $X_{cn} \to l_{Gn}$, there should be $\Omega_n \to 0$ and $\Delta x_n \to 0$. This trend is taken into account in our model using a feedback function f_n:

$$f_n = \left[1 - X_{cn}/\left(l_{Gn} - l_c\right)\right]^{0.5}, \quad X_{cn} \geq 0, \quad (28)$$

which, as an additional factor, is included in dependence (21), as well as in the first terms on the right-hand side of dependences (24) and (25). The beach width X_{cn} is calculated by summing the elementary displacements Δx_n, which decrease with each time step. The beach grows until an equality $X_{cn} = \left(l_{Gn} - l_c\right)$ or $X_{cn} = \left(l_{Gn+1} - l_c\right)$ is reached, meaning filling of the intergroin space S_n and termination of accumulation ($b_n = 0$ or $b_{n+1} = 0$).

Displacements of the beach beyond the field X_{c0} and X_{cN} reflect the average changes within length L. However, in the case of accumulation, beach advancement directly at the structure is twice as large as the average [2, 5]. Therefore, achievement of conditions $X_{c0} = 0.5\left(l_{G1} - l_c\right)$ or $X_{cN} = 0.5\left(l_{GN} - l_c\right)$ means filling of the re-entrant corner at the first or last groin, which therefore ceases to be an obstacle to alongshore sediment transport ($b_1 = 0$ or $b_N = 0$). To track these conditions in the calculations, it is recommended to use a time resolution of ~0.1 year.

Table 1. Experimental conditions in wave tank [9] and modeling results

Test	h_G, m	l_G, m	λ, m	Ω_1, m^3	h_*, m	l_*, m	b	Λ, m	K	Ac, m^3/h	$\Omega_1^{(c)}$, m^3
NT3	0.10	2.0	3.2	0.01	0.133	2.3	0.75	2.14	0.75	0.0014	0.011
NT5	0.07	1.6	2.6	0.02			0.53	1.92	0.68	0.0024	0.019

As an illustration, we give several examples of a three-year forecast of changes in a sandy seashore under the influence of a groin field consisting of five elements (Fig. 4). We characterize the shore profile with fairly typical parameters: $h_* = 7$ m, $z_c = 1$ m, $l_* = 350$ m, $l_c = 10$ m (see Fig. 1).

The base length of the structures is $l_G = 30$ m, the depth at the end $h_G = 1$ m, the step of the field is $\lambda = 120$ m, and sediment migrates either only in one direction (test 1: $Q_{0\Sigma} = 40000$ m^3/year), or in opposite directions (tests 2–6: $Q_{0\Sigma} = 40000$, $Q_{N\Sigma} = 20000$ m^3/year).

In test 1, after 3 years, the re-entrant angle is filled in front of the first groin, which accelerates accumulation in the adjacent intergroin space. Downdrift erosion exceeds 25 m. In test 2, the accumulative volume inside the groin field increases and erosion decreases. Clearly, with two-way supply, the negative influence of the groin is noticeably less.

In test 3, the initial data are the same, with the exception of the step of the field λ, which is increased 1.5-fold (up to 180 m). In this case, the rate of beach growth inside the field decreases several times, which emphasizes the role of parameter λ.

Test 4 increases the length of groins ($l_G = 45$ m) and depth at their ends ($h_G = 1.5$ m). As a result, accumulation in the field increases, as well as the extent of the areas of influence of structures.

Tests 5 and 6 pertain to heterogeneous groins that are sequentially truncated toward the right margin of the field. It is believed that such a measure helps to reduce downdrift erosion [8, 11]. In test 5, the erosion is indeed less than in similar test 2 with homogeneous groins, but accumulation is also reduced.

The conditions of test 6 are the same, but the forecast time is tripled (up to 9 years). By this time, the intergroin spaces are completely filled, sediments bypass the structures from the outside, the downdrift erosion ceases and the position of the shoreline stabilizes.

The above results clearly demonstrate the possibility of regulating the influence of groins by changing their parameters. Note that the contour of the shoreline in the zones of influence of a structure can be determined using model [5].

VERIFICATION OF THE MODEL

To verify the model, we applied published laboratory and field data.

Wave tank example. The morphological effect of groins was considered in experimental study [9]. In one of the tests, an initially flat sandy beach slope was subjected to 12-h irregular wave action (significant wave height 0.08 m, spectral peak period 1.15 s, angle of approach 11.6°), as a result of which a stable relief developed. It served as a reference for comparisons with the relief formed in presence of two impermeable groins. The alongshore sediment transport averaged 48 kg/h, which for standard sand density and porosity values corresponded to a volumetric transport of $Q_0 = 0.030$ m^3/h.

The experimental conditions are presented in Table 1. For comparison, two tests (NT3 and NT5) were selected that satisfy the requirements of the model $l_G/l_* < 1$. The groin parameters and accumulation volumes in the intergroin space Ω_1 are determined from the graphs in [9].

The right side of Table 1 presents the calculated model parameters. The closure depth h_* is taken equal to that h_B determined by formula (17). The last column of the table shows the estimated accumulative volumes $\Omega_1^{(c)}$, which are clearly quite close to the measured values Ω_1. The results obtained confirm the previously noted tendency toward an increase in the accumulation rate Ac for $b \to 0.5$, as well as with a decreasing K value.

Example of India's Southwest Coast. Study [14] describes an experiment using groins to grow a sandy beach on an eroded stretch of India's southwest coast. The shoreline here directly approached a previously constructed protective wall (Fig. 5). After two groins were constructed, the beach began to grow rapidly, especially on the outer side of Groin G_1 facing the dominant sediment flux (70000–100000 m^3/year).

As Fig. 5 shows, 5 years after construction of the groin, the shore advanced to the end of the first one. Downdrift erosion apparently migrated to an area beyond the protective wall.

In the calculations, the following shore profile and groin parameters were taken: $Q_{0\Sigma} = 85000$ m^3/year, $h_* = 7$ m, $l_* = 300$ m, $z_c = 0$, $l_c = 0$, $l_G = 35$ m, $h_G = 0.7$ m, and $\lambda = 150$ m. Figure 5 also shows the predicted po-

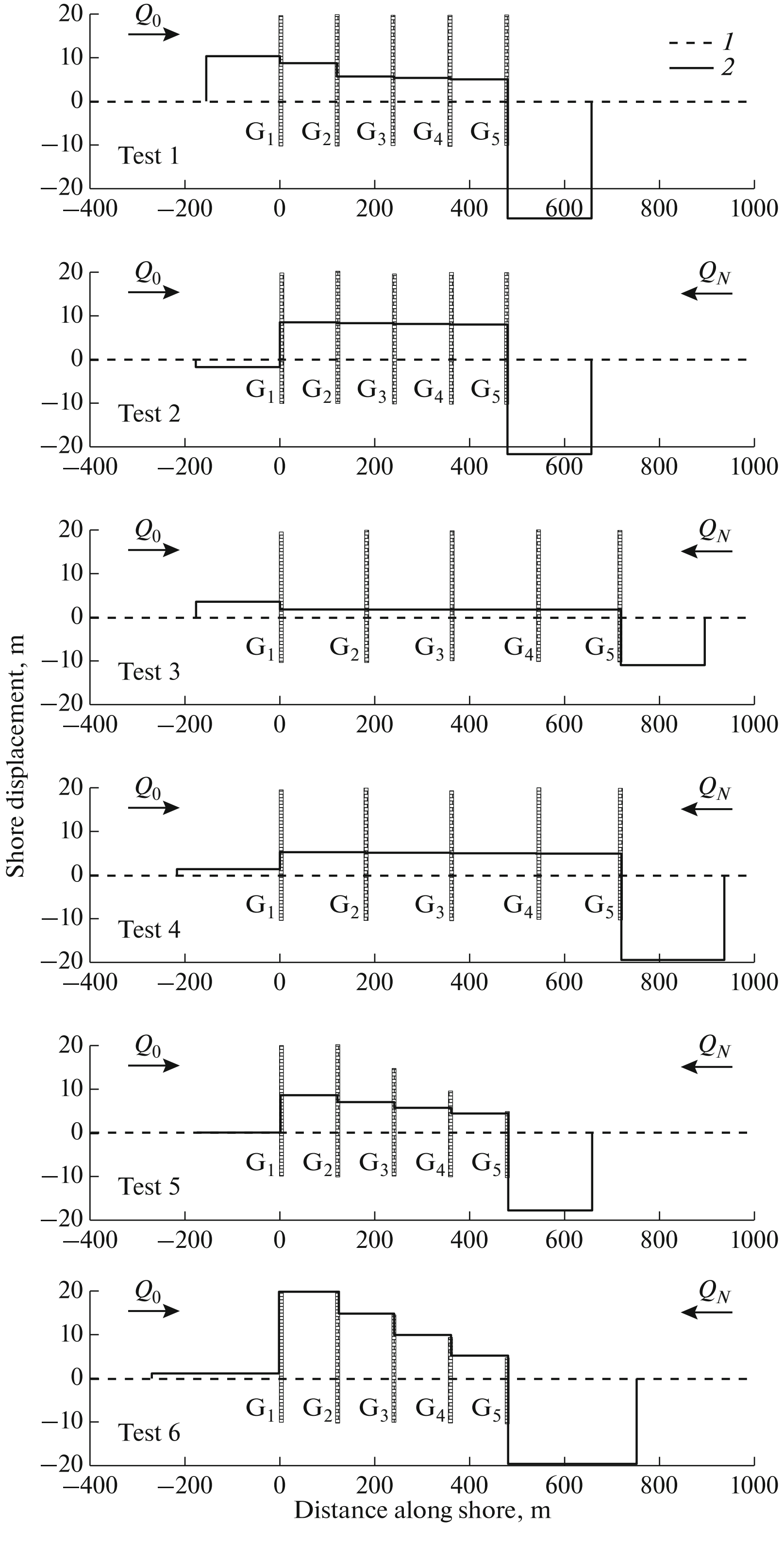

Fig. 4. Examples of forecasting changes in sandy beach under influence of groin field. (*1*) Initial shoreline; (*2*) average beach position 3 years after construction of groins (for test 6, after 9 years). See text for initial data.

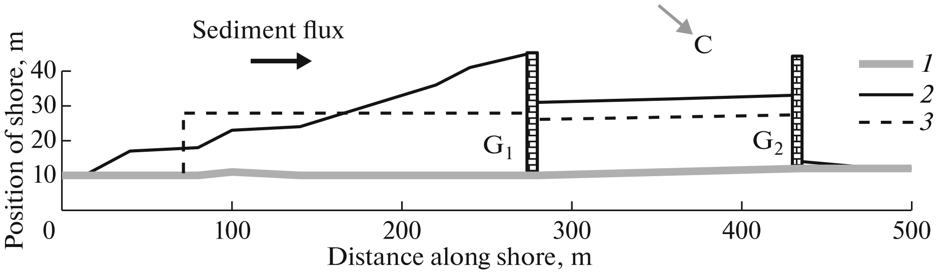

Fig. 5. Changes in under influence of groins (southwest coast of India [14]). (*1*) Protective wall marking position of edge in 2009; (*2*) position of shoreline recorded in 2014 (after construction of five groins); (*3*) average beach migrations according to calculations.

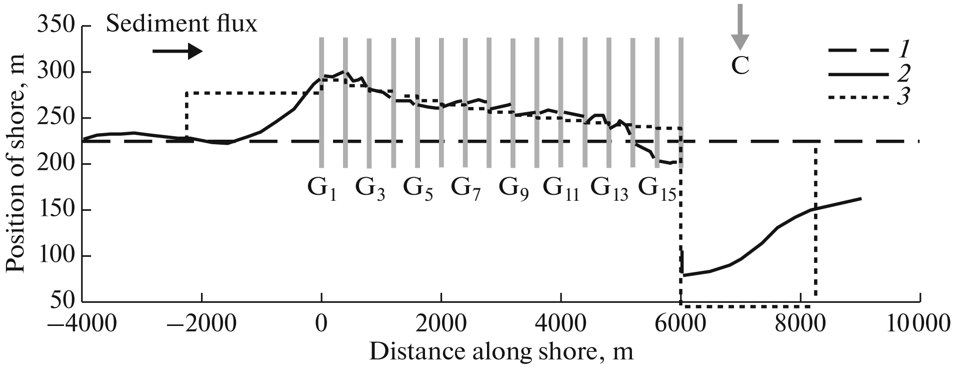

Fig. 6. Beach evolution at Westhampton Beach, Long Island [7, 13]. (*1*) Conditional initial 1965 shoreline; (*2*) 2015 shoreline corresponding to forecast [13]; (*3*) same in accordance with our model.

sition of the shoreline. According to the calculations, in 3.5 years, the beach should have advanced to the end of the first groin, which should have accelerated accumulation in the intergroin space. Predicted and measured shore beach displacements are on the same order.

Example of the coast of Long Island. We are dealing with the coastal area of Westhampton Beach, where a field of 16 groins was built to protect against storm erosion (Fig. 6). Construction began in 1965 and lasted several years.

In this case, the object of comparison is the 2015 shoreline predicted by model [13] based on the initial data from 1995 (Fig. 6). In our calculations, the conditional straight line of the beach was taken as the basis, which presumably reflects its average position in 1965; thus, the period of our forecast is 50 years. The following shore and groin field parameters were used: $Q_{0\Sigma} = 100000$ m^3/year, $l_* = 8$ m, $l_* = 700$ m, $z_c = 3$ m, $l_c = 30$ m $l_G = 145$ m, $h_G = 2.5$ m, and $\lambda = 400$ m. The actual parameters of individual groins differ from each other somewhat, but in the calculations, they were assumed to be homogeneous.

Figure 6 shows that the most significant differences in the calculation results for the two models are seen on the left margin of the field (Groin G_1), where our model overestimates accumulation, as well as on the right margin (groins G_{14}–G_{16}), where model [13] predicts erosion. Otherwise, both calculated shorelines replicate each other.

CONCLUSIONS

The proposed model explains accumulation in the groin field from the standpoint of the law of mass conservation. Sedimentation in the intergroin spaces is associated with the gradient of the alongshore sediment flux passing through the groin field. The rate of the process is controlled both by the flux and parameters of the structures. The time scale of modeled morphological changes varies from several hours (individual wave situations) to several years.

One of the key parameters of the model is the extent of the zone of influence of a structure Λ. The accumulation rate in the groin field is maximum when the intergroin distance is close to Λ. If the indicated distance reaches 2Λ, then sediment accumulation in the intergroin space ceases.

Although quantity Λ is quite conditional, introducing it helps to simplify analysis of the problem and find the optimal relations between the step of groins λ, their length l_G, and the width of the active area of the shore profile l_*. For short groins (l_G/l_* about 0.1), the optimal step is close to $3l_G$, whereas for long structures (l_G/l_* about 0.5), it is $1.4l_G$.

The length of groins is closely related to another parameter of the model, *b*, characterizing the fraction of sediment flux intercepted by the groin. The maximum accumulation corresponds to a value of $b = 0.5$, implying that a groin ends at a depth half that of the closure depth. This, however, seriously interferes with natural processes. To reduce the level of impacts, it seems better to use shorter groins corresponding to lower *b* values, which is feasible for economic reasons.

The main indicators of a groin-related project are the accumulative volumes, the expansion of the beach, and downdrift erosion at a given point in time. The above examples of calculations demonstrate the possibility of controlling the groin field parameters to achieve the set goal and reduce undesirable effects. The latter can be achieved by introducing an additional amount of material into the intergroin spaces.

For a short-term forecast, in some cases, the condition of homogeneous accumulation of sediment and beach growth in the intergroin spaces is acceptable. However, as the edge of the beach approaches the head of a groin, accumulation should slow. This tendency is taken into account in our model by including a feedback function, which depends on the ratio of the current beach width to the groin length. The calculation results are mainly confirmed by published observation data.

FUNDING

The study work was carried out as part of a state task (topic no. 0149-2019-0005) with partial support from the Russian Foundation for Basic Research (project nos. 18-55-3402 Kuba_t, 18-05-00741).

REFERENCES

1. I. O. Leont'yev, *The Dynamics of the Surf Zone* (Shirshov Institute of Oceanography, Academy of Sciences of the USSR, Moscow, 1989) [in Russian].
2. I. O. Leont'yev, "Changes in the shoreline caused by coastal structures," Oceanology (Engl. Transl.) **47**, 877–883 (2007).
3. I. O. Leont'yev, *Morphological Dynamics in the Coastal Zone of the Sea* (LAP LAMBERT Academic, Saarbrücken, 2014) [in Russian].
4. I. O. Leont'yev, "Calculation of longshore sediment transport," Oceanology (Engl. Transl.) **54**, 205–211 (2014).
5. I. O. Leont'yev, "Changes in shoreline contour due to cross-shore structure in the sea coastal zone," Geomorfologiya, No. 3, 32–39 (2018). https://doi.org/10.7868/S0435428118030033
6. V. M. Peshkov, *Coastal Sea Zone* (Lakont, Krasnodar, 2003) [in Russian].
7. Z. Prushak, R. Ostrovskii, A. N. Babkov, and B. V. Chubarenko, "The main principles of bank stabilization by the groins," Geomorfologiya, No. 3, 91–104 (2014).
8. *SP 277.1325800.2016: Design Rules, Costal Protection Constructions* (Ministry of Construction Industry, Housing and Utilities Sector, Moscow, 2016) [in Russian].
9. P. Badiei, J. W. Kamphuis, and D. G. Hamilton, "Physical experiments on the effects of groins on shore morphology," in *Proceedings of the 24th International Conference on Coastal Engineering, Kobe* (American Society of Civil Engineers, Reston, VA, 1994), pp. 1782–1796.
10. M. Capobianco, M. Larson, R. J. Nicholls, and N. C. Kraus, "Depth of closure: a contribution to the reconcillation of theory, practice and evidence," in *Proceedings of the International Conference "Coastal Dynamics'97," Plymouth* (American Society of Civil Engineers, Reston, VA, 1997), pp. 506–515.
11. *Coastal Engineering Manual (CEM)*, Part V, Chap. 3: *Shore Protection Project No. EM 1110–2–1100* (U.S. Army Corps of Engineers, Washington, DC, 2002).
12. H. Hanson, "GENESIS: a generalized shoreline change numerical model," J. Coastal Res. **5** (1), 1–27 (1989).
13. H. Hanson, M. Larson, and N. C. Kraus, "Calculation of beach under interacting cross-shore and longshore processes," Coastal Eng. **57**, 610–619 (2010).
14. V. Noujas, K. V. Thomas, and N. R. Ajeesh, "Shoreline management plan for a protected but eroding coast along the south-west coast of India," Int. J. Sediment Res. **2**, (2017). https://doi.org/10.1016/j.ijsrc.2017.02.004i
15. J. Schoonees, A. Theron, and D. Bevis, "Shoreline accretion and sand transport at groynes inside the port of Richard Bay," Coastal Eng. **53**, 1045–1058 (2006).
16. V. Süme, "Shoreline changes in three groin fields on the eastern Black Sea coast," Fresenius Environ. Bull. **28** (1), 125–131 (2018).