THE THEORETICAL BASES OF PORT AREAS AND ACCESS CHANNELS DEPOSITION CALCULATION

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The paper discusses the configuration options of port waters and channels affected by deposition in coastal flow of sediment transport (with/without waves). Performed typing the possible configuration options structures, hydro- and litho-dynamics conditions that lead to reducing the depth of areas and channels. Proposed the engineering method of port areas and channels deposition calculating depending on their configuration, nature and intensity of currents.

Key words: port waters, navigation channels, dredging, waves and currents alongshore sediment transport, deposition.

I. Introduction

When designing ports, one of the important tasks is to forecast deposition in port waters and approach channels, sandy or pebbly sediments. On the basis of the forecast are determined the frequency and volume of maintenance dredging works.

In the modern literature largely discussed the deposition of approach channels to ports [1-14] and several lesser the deposition of port areas [15-18].

In all the works it is noted that the deposition of approach occurs as a result of speed reduction of alongshore current over the channel due to the increase of depth and, respectively, reduce the carrying capacity of the water flow. In addition, port facilities solid structures may stop completely or partially of alongshore sediment transport with the formation of accumulative forms. In the number of works [9, 11-14, 17-18] for some configurations of hydraulic structures describes physics of the process. However, the classification (typing) options deposition in port waters and approach channels, as well as the general engineering method of calculation is missing.

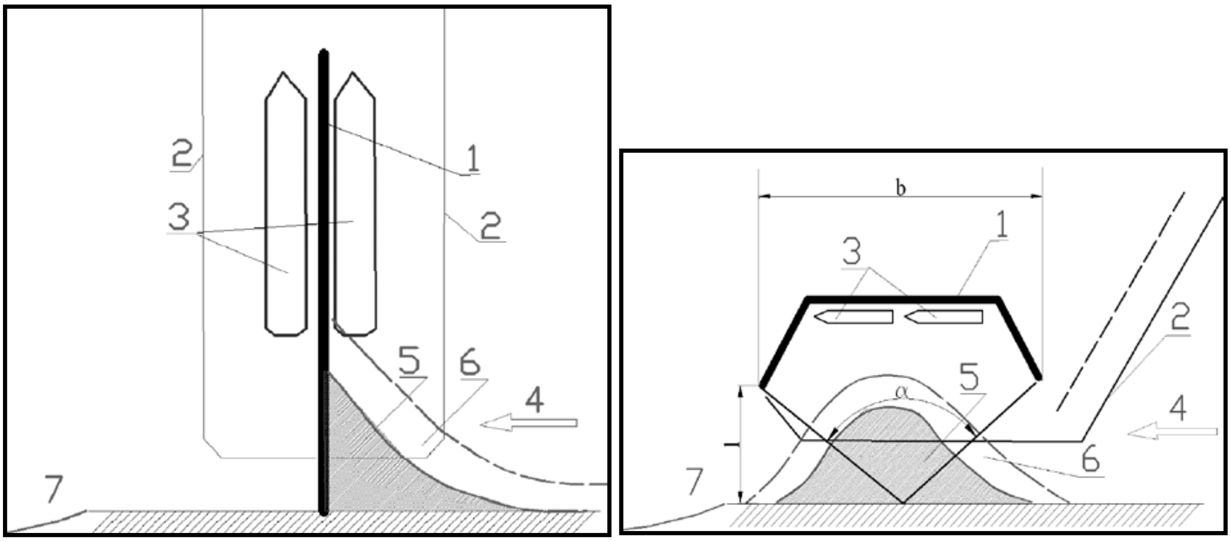
II. Classification of structures configurations, at which there is a deposition of water areas and channels

Deposition in port waters and approach channels occurs for the following reasons:

1. The interception completely or partially of alongshore sediment transport by port moles of solid structure with the formation in the waters of the berths of accumulative forms of the type "incoming angle" – Fig. 1, *a*). In such instances when unidirectional sediment transport may occur grassroots erosion of the shore. In the case of multi-directional sediment transport, incoming angles are formed on both sides of the mole.

2. Unloading of an alongshore sediment transport in a wave shadow of island port with formation of spit – Fig. 1 *b*). In such cases at the unidirectional alongshore stream of deposits,

there is a local washout of the coast. In case of multidirectional streams of deposits, the spit can degenerate in tombolo (connected with breakwater).

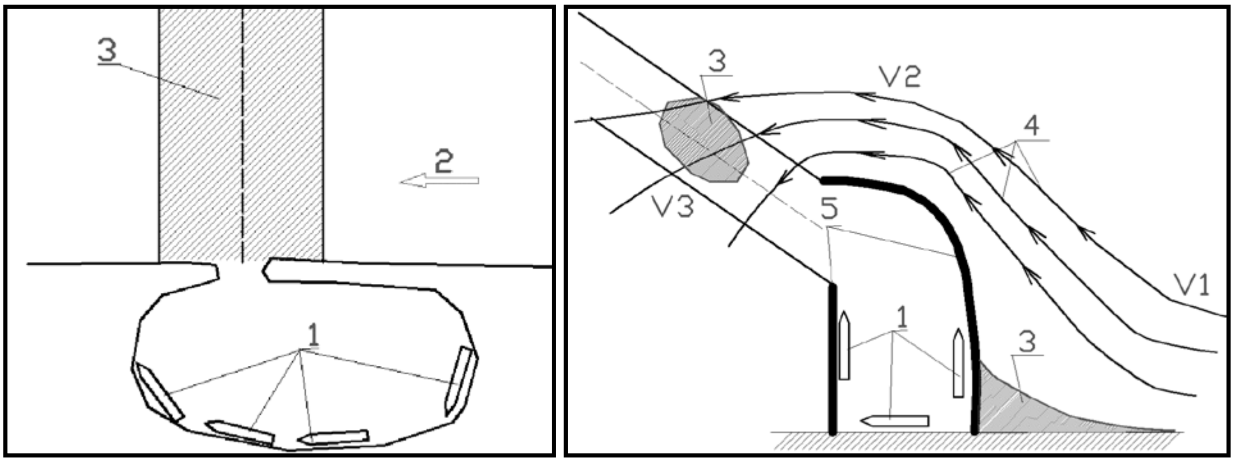


a) *b)*

Fig. 1. Deposition of water of the mole-pier of solid construction a) and water of the island port b); 1 – hydraulic structure, 2 – borders of dredging, 3 – ships, 4 - alongshore sediment transport, 5 – surface part of the sediment load, 6 – the underwater part of the sediment load, 7 – grassroots erosion of the shore.

3. Unloading of alongshore sediment transport on the approach channel when reducing the speed of current at the expense of increase in the area of its live section on dredging of the channel – Fig. 2 *a)*.

4. Unloading of an alongshore sediment transport in the water area of dredging or on the approach channel at reduction of speed of an alongshore current as a result of at first its narrowing with increase in speed and, respectively, a stream turbidity, and then its expansion with reduction of speed and loss of deposits. Arises at considerable promotion of protective piers in the sea concerning the line of the coast - Fig. 2 *b)*. Thus additional reduction of current is caused also by increase in depths in dredging zones.

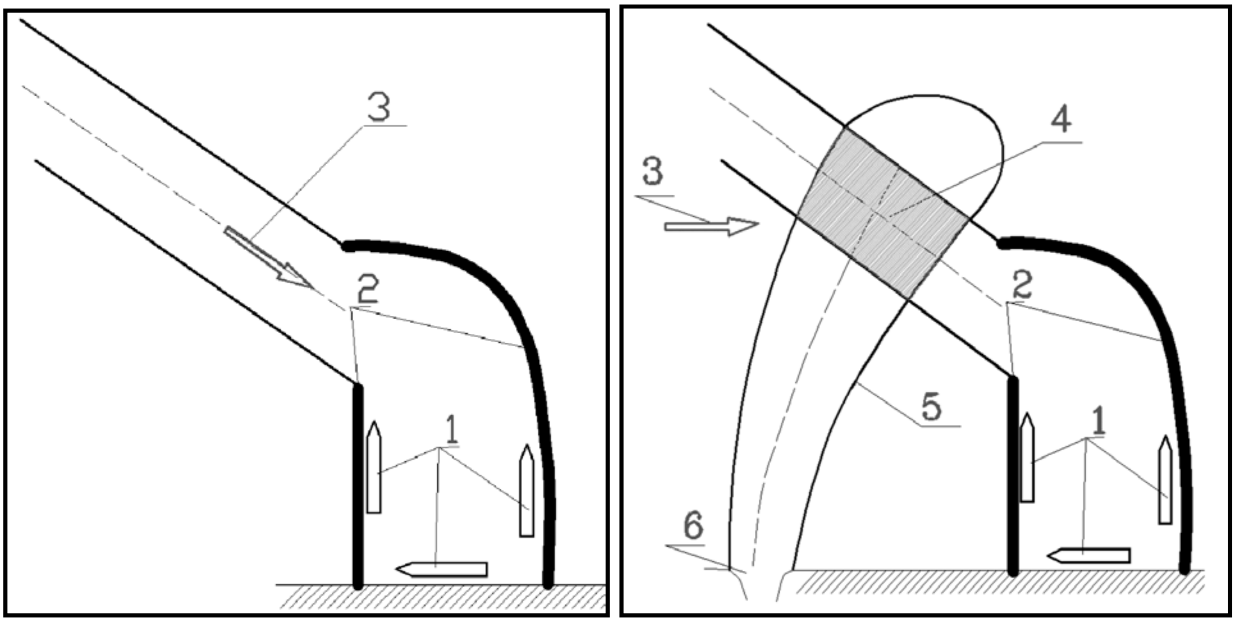


a) *b)*

Fig. 2. Deposition of approach channel as a result of decreasing flow velocity over the channel a) and as a result of expanding of current and increasing the depth on the channel; 1 – ships, 2 – alongshore sediment transport, 3 - accumulation of sediment, 4 – line of flow, 5 – moles.

5. Deposition of port water as a result of the ingress of sediment under the influence of wave and wind currents – Fig. 3 *a)*.

6. Deposition of dredging water area, or of the approach channel by sediments of the river flood jet – Fig. 3 *b)*.



a) *b)*

3. Deposition of the port waters as a result of the total wave and wind currents a); deposition of the approach channel by flood stream of the river rejected by alongshore current b);1 – ships, 2 – moles, 3 – current, 4 – zone of deposition of channel, 5 – boundaries of the jet of river flooding, 6 – mouth of river.

It should be noted [23] that the waves and currents have the opposite effect on alongshore sandy sediment transport in the vicinity of cross shore constructions.

Under the influence of slantwise suitable waves sandy sediments tend to form a cross before the construction of the "incoming angle", that is accumulative form. At the grass-roots plot has place grass-roots erosion due to sediment deficit in alongshore current.

At the same time, current is forms of the cycle before the construction, seeking to erode the shore. Skirting the structure with sea side during "tapering" and its speed increases, it becomes saturated with suspended sediment. After bypass construction, the jet of flow expands, its velocity decreases and the sediment fall out in the head part of the structure on the leeward of him. With bottom-side of construction is formed the second cycle, seeking to form an accumulative form.

III. Models of hydro- and litho-dynamics of a coastal zone of the sea

For modeling of port water areas deposition it is necessary to define the settlement equations describing the physical processes given above.

The estimated waves elements in the coastal zone can be determined in accordance with [29, 32].

For calculation of wave alongshore transport of pebble deposits the dependence recommended in the normative document [34] can be used. For deposits with an average diameter of $d_{50\%}\geq 2$ mm the transporting ability of a wave stream (capacity of an alongshore sediment transport) is determined by equation:

$$Q_e = 0.087\frac{\rho}{\rho_s} g \frac{h_{cr1\%}^3 T\Delta t}{k_{ok} d_{50\%}} sin2\alpha_{cr} \tag{1}$$

where $h_{cr1\%}$ - height of a wave of 1% probability in system in the area of the last wave breaking, ρ_s - the volume weight of deposits, ρ - the volume weight of water, g – gravitational acceleration, T - the average period of waves, $d_{50\%}$ - the median diameter of beach material, Δt - time of action of waves, k_{ok} - coefficient of pebbles roundness [34], α_{cr} – angle of approach of waves to the line of the last wave breaking.

For the sand sediment in account with [35]:

$$Q_e = 0.035\Delta t(\frac{h_{cr}}{d_{cr}})^2 \rho g d_{cr} V_{cp} \frac{tg\varphi_0(1-(V_{ac}/V_{av})^{3/2})}{(1+3/8(h_{cr}/d_{cr})^2)}, \tag{2}$$

where d_{cr} – depth of wave breaking, V_{ac} - velocity of an alongshore current, average on depth, V_{av} – competent velocity, $tg\varphi_0$ - the slope of beach balance, determined by formulas:

$$tg\varphi_0 = \frac{tg\varphi_e}{1+\left[ln\left(\frac{h_{cr}}{d_{50\%}cos\alpha_{cr}}\right)lg\left(10^5\frac{h_{cr}}{gT^2}cos\alpha_{cr}\right)\right]}, \tag{3}$$

$$tg\varphi_e = 1 - 0.8ln\frac{1}{d_{50\%}\left(\frac{\rho_s}{\rho}-1\right)}, \tag{4}$$

where $tg\varphi_e$ - average bias of a natural slope of material of deposits in quiet water; h_{cr} - height of waves of 30% probability in system of estimated storm at the first wave breaking

Pebble deposits move along the coast in slip or saltation. That is, practically, without coming off a bottom. Thus movement of deposits happens between the line of the last waves breaking and border of their run up on the coast. The maximum of movement of deposits takes place on shoreline and linearly decreases to the line of waves breaking and border of a run up – Fig. 4. Width of the front of transfer of pebble deposits usually doesn't exceed 100 – 150 m from shoreline.

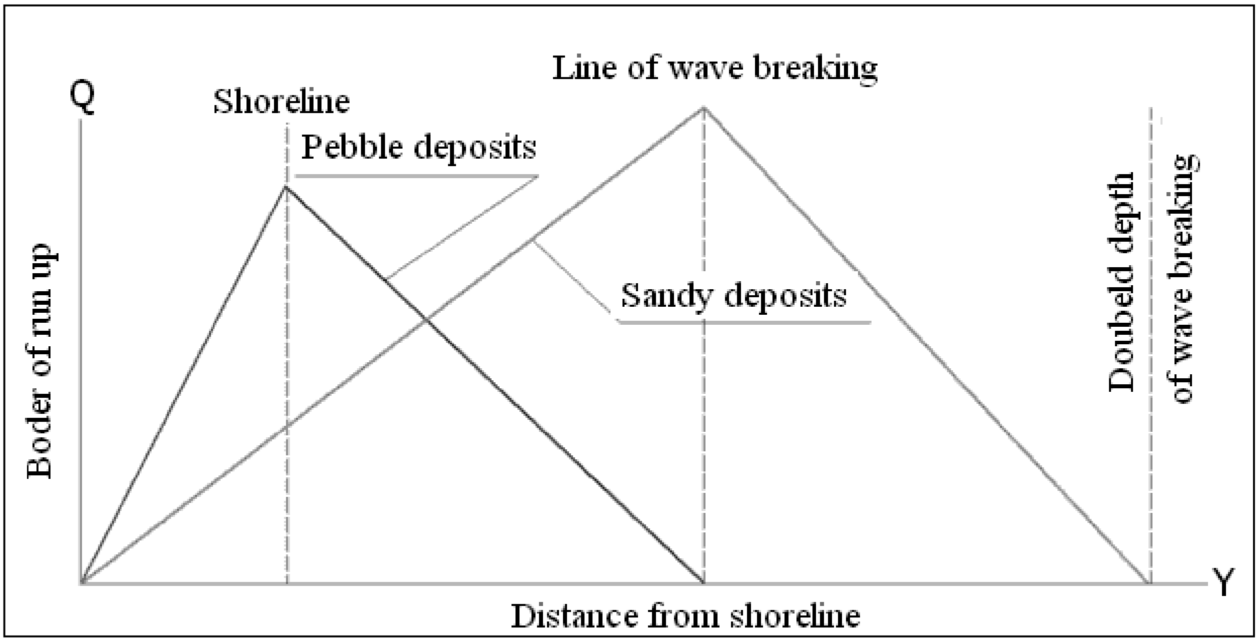


Fig. 4. The schematized diagrams of alongshore transport of pebble and sandy deposits.

Sandy deposits move at the front between border of wave run up and distance from the coast where depth makes the doubled depth of the first wave breaking (width of the front of transfer of sandy deposits can reach 1 km and more). The maximum of movement of sandy deposits by excitement is concentrated on the line of wave breaking – Fig. 4.

Influence of a breakwater of island port (Fig. 1 b) on alongshore wave sediment transport can be estimated by calculation of coefficients of diffraction of waves behind a breakwater [32]:

$$k_{dif} = \sqrt{k_{dif1}^2 + k_{dif2}^2}\ , \tag{5}$$

where k_{dif1}, k_{dif2} - coefficients of diffraction of waves on head parts of breakwater. In formulas (1) - (3) it is necessary to substitute $h_{dif} = k_{dif}h_{cr}$ and the corresponding depth of wave breaking. Detailed research of this question is executed in work [36].

Surface velocity of drift (wind) currents V_{sf} in the coastal zone are calculated by the method proposed by Ekman and recommended in normative literature [29]. Average in vertical velocity of drift currents in the coastal zone can be defined based on the availability of surface waves by the formula:

$$V_{av} = 0.35V_{sf}[2 - lg\left(\frac{d}{\lambda}\right)], \tag{6}$$

where d is the depth, λ - the average length of surface waves. Approximately $V_{av}/V_{sf} \approx 0.3$.

The transfer (Stokes) wave current in a shallow zone extends in the direction of a wave ray with velocity (formula by Longe-Higgins) [30]:

$$V_{tr} = \left(\frac{5}{4}\right)(a^2mk)/(sh(md)^2), \tag{7}$$

where $a = h/2$ - wave amplitude, d - depth, $m = 2\pi/\lambda$, $k=2\pi/T$, T - wave period, λ – wave length.

In the surf zone velocity of transfer current can be calculated according to empirical relationship:

$$V_{tr} = \sqrt{0.333d\left(\frac{h}{d}\right)^2}. \tag{8}$$

The currents caused by various height of wind and wave onset in a coastal zone are called gradient. Gradients of level and, respectively, pressure result. Pressure gradient actually is also the reason of gradient currents. After definition of marks of level of a free surface, calculation of gradient currents can be executed according to recommendations of Shadrin [31].

At calculations of a turbidity of water (the maintenance of a suspension) the limit turbidity of water C, average on depth, kg/m^3 can is determined by a known formula of Rossinsky [26]:

$$C = K_mV^3/(gdW_d), \tag{9}$$

where K_m - empirical coefficient, K_m = 0.24, V - depth-averaged horizontal fluid velocity, d - depth at the point or depth where the average depth velocity is not less than 20% of the surface velocity, W_d – settling velocity of sediment.

Discharge of bottom and suspended sediments from the total currents (Stokes, drift and gradient) per unit width of the front of their transport (m^2/s) is defined by I. Levi [36].

To calculate the distribution of the river flow in the coastal zone in the presence of alongshore current, the special method is developed [37], which implements the theory of turbulent planar jet in a drifting stream [28].

Deposition of port water areas with formation of "incoming angle". To evaluate the deposition of moorings water area by wave long shore sediment transport in the presence of cross structures impenetrable construction (Fig. 1 *a*), it is necessary to calculate the sediment discharge $Q_{m,i}^{j}$ from the formulas (1) - (4), for each *i* wave dangerous direction and *j* gradation of wave height which has a length Δt_i^j and determine the amount of sediment runoff in an average year:

$$W_{ay} = \sum Q_{m,i}^{j} \Delta t_i^j. \quad (10)$$

At the same time duration in days of waves from every directions and gradation of wave height is determined by the wind rose:

$$\Delta t_i^j = P_i^j N, \quad (11)$$

where P_i^i - the repeatability of the unrest in the unit shares on average per year, *N* - the length of the ice-free period in days on average per year.

Next, the width of the front sediment transport (the distance to the last line of wave breaking for gravel deposits or distance to twice the depth of the first wave breaking for sandy sediment) and sediment discharge the diagram (Fig. 4) estimated the average annual share of that falls into the waters of berths W_{ak}. When the area of water recorded as S_{wa}, the average reduction of the depth will be

$$\Delta d_w = \frac{W_{ak}}{S_{wa}}. \quad (12)$$

If necessary, according to formulas (10) - (12) it can be determined the deposition in storms of rare repeatability.

Deposition of island port water areas. As shown in [36], deposition of water of the island by alongshore sediment transport occurs at $l<3b$, where *l* - the distance from the shoreline to breakwater of island port, *b* is the length of the breakwater along the coast (Fig. 1 *b*).

If this ratio indicates the possibility of deposition waters of island port, it must first be calculated the coefficients of diffraction of waves for each gradation in each direction - $K_{dif,i}^{j}$ using the formula (5), Next, calculate the amount of the average annual inflow W_{ayi} by the formula (10) and removal of sediment from the water area of the port of the island:

$$W_{ayr} = \sum Q_{m,.b,i}^{j} \Delta t_i^j, \quad (13)$$

where $Q_{m.b,i}^{j}$ - the discharge of sediment taking into account diffraction of waves on breakwater of island port. The volume of deposition and depth reduce of the waters in the port area of the island S_{ak} is determined by formula:

$$\Delta W_{ay} = W_{ayi} - W_{ayr}, \quad (14)$$

$$\Delta d_{is} = \frac{\Delta W_{ay}}{S_{ak}}. \quad (15)$$

Deposition of berths or approach channel waters not narrowing of alongshore current by cross structure. When calculating the deposition of berths or approach channel waters not hesitate of alongshore current by cross structure (Fig. 2 *a*), it is assumed that to it is approach the alongshore current with discharge of water per unit width:

$$q_n = V_n d_n, \quad (16)$$

where V_n - total rate of alongshore current on the way to the waters of dredging (channel) with a depth d_n.

Above the water area dredging with a projected depth of $d_{dr} = d + \Delta d$, where Δd - the volume of dredging, velocity of current with same discharge is rate falls to:

$$V_{dr} = \frac{q_n}{d_{dr}}. \quad (17)$$

Consequently, the sediment discharge in dredging zone defined by taking into account the velocity V_{dr} is set to q_{dr}. The difference of sediment discharge, which determines the deposit of water area:

$$\Delta q_{dp} = q_n - q_{dr}. \quad (18)$$

Then the volume of deposition ΔW_{dp} and the average reduction in the depth Δd_{dp} the waters wide flow of sediment B in an area S_{ak} during time T will be:

$$\Delta W_{dp} = \Delta q_{dp} BT, \quad (19)$$

$$\Delta d_{dp} = \frac{\Delta W_{dp}}{S_{ak}}. \quad (20)$$

Duration T of alongshore currents varying speeds from each direction is determined by a rose flows according to field observations or calculated by the wind rose.

Narrowing of alongshore current by cross structure. In case of narrowing of alongshore current by cross structure (Fig. 2 *b*), it is necessary to estimate the width of stream (front of sediment transport) B_{fr}, testing influence of building. In hired from data of model supervisions on the Kaliningrad coast of the Baltic sea, this size is accepted equal $B_{fr} = 1.5L_{cc}$, where L_{cc} is length of continuous part of construction.

Calculation of water deposition as a result of the narrowing and subsequent expansion of alongshore current execute the following statement. To the pier area with width of front B_{fr} enters the alongshore current at a speed V_n. Flow rate:

$$Q_n = V_n B_{fr} d_{av}, \quad (21)$$

where d_{av} – average depth on width of front.

When approaching the head portion of a structure the velocity of flow is increased to the value:

$$V_s = \frac{Q_п}{0.5L_{cc} d_{dr}}, \quad (22)$$

where d_{dr} – depth at the head of the structures based on dredging.

The specific consumption of the sediment surrounding the construction of the flow will be q_c. Full sediment discharge:

$$Q_c = 0.5 q_c L_{cc}. \quad (23)$$

After crawling head part of the construction, the stream expands to a width of L_{cc}, while its speed drops to a value

$$V_o = \frac{Q_c}{L_{cc} d_a}, \quad (24)$$

where d_a is water depth after structure with subject to dredging.

Accordingly, the specific sediment discharge in the stream after bypass their structures will be equal to q_o, the total sediment discharge:

$$Q_o = q_o L_{cc}. \quad (25)$$

Then the value of deposition ΔW_d and an average reduction of the depth of the waters Δd_{dp}, located on the leeward side of the pier width X_s, length L_{cc} during time T will be:

$$\Delta W_d = (Q_c - Q_o)T, \quad (26)$$

$$\Delta d_{dp} = \frac{\Delta W_d}{L_{cc}\ X_s}. \quad (27)$$

Deposition in waters through the gates of the port. Deposition in port waters via its gate (Fig. 3 *a*) is considered for two cases. The entrance gate of the port width of B_p with depth d_p may be located outside the surf zone (major ports), protection structure when submitted to a considerable depth, and in the surf zone (small ports and yacht harbours).

In the first case, deposition of the port water area is determined mainly by the amount of drift and Stokes wave flow V_{sum}, which are calculated by formulas (6), (7).

The specific sediment discharge q_p, penetrating to the waters of the port and the calling deposition in its water area S_p is defined by the formula I. Levy. The full sediment discharge Q_p, and their volume W_p and reducing the depth at the port Δd_{dp} after time T given the action of the hydrometeorological situation (speed and wind direction) are determined by the expressions:

$$Q_p = q_p B_p, \tag{28}$$

$$W_p = Q_p T, \tag{29}$$

$$\Delta d_{dp} = \frac{W_p}{S_p}. \tag{30}$$

To determine the average deposition in the port water area it is necessary to calculate the duration of action of various meteorological situations using the wind rose and summarize the results obtained for them by the formulas (28)-(30).

If it place the entrance gate of the port in the surf zone to pebbly sediments or within the riparian zone width to twice the depth of the first caving of the waves to the sandy sediment, their long-term average flow is determined by the formulas (1), (2). Further be plots which are shown in Fig. 4 is determined by the volume of sediment transported W_p entering the gate port and the equation (30) calculated a mean annual decrease of the depth in the port basin as a result of deposition.

Deposition of port waters and channels by the solid runoff of rivers. Deposition of port waters and approach channels by the solid runoff of the rivers (Fig. 3 *b*) occurs typically during major floods on the rivers flowing into the sea near the location of port facilities.

Therefore, to calculate the deposition in the port water area is necessary, first, to calculate the discharge Q_0 of the liquid and solid Qs flow [25], and velocity of flows of river at its confluence into the sea U_0. Turbidity jet of C_0 at the mouth of the river is determined by the formula (9). In addition, it is necessary to determine the duration of the flood T_r.

On the sea the river turns into a turbulent inertial jet. Friction on the bottom and the interaction with sea water leads to an overall reduction in jet velocity and its spread. River deposits, falling into the region of speeds, lower shift speed, start to accumulate in the form of the alluvial cone. The growth of accumulative the body, the flow meets increasing resistance, loses the stability under the action of waves and coastal currents strays to one side depending on the direction of alongshore current.

Calculation of distribution of the river flow near the port water area to estimate average annual deposition of its water area should be made for flood of annual repeatability, in combination with the most adverse speed and direction of alongshore current carrying flood stream toward the port.

Velocity of alongshore currents can be defined as according to direct observations, as calculated on the wind speed. In the latter case, the calculation is performed according to the formulas (6) to (8).

Next is calculated the trajectory of the river jet in the coastal zone [28, 37]. Turbidity in a jet is determined at any point by the formula (9). Therefore, in the area of dredging in connection with increasing depth of the turbidity in the part of the jet, which lands on the waters, will decrease the value of C_{jet} on the approach to the area of dredging, to the value C_{dr} in this area.

Then the volume of deposition in area of dredging, which crosses the jet will be determined by the formula:

$$W_{dr} = \frac{Q_{dr}(C_{jet} - C_{dr})T_r}{\rho_s}, \qquad (31)$$

where ρ_s - density of river sediment.

Reducing the depth Δd_s in area of S_{jet} in the zone of penetration of the river jet is determined by the formula (30).

On the elaborated methods was calculated deposition approach channels and operating water areas of the coal port "Sukhodol" in the Bay of Telyakovskiy, Peter the Great Bay sea of Japan (Vladivostok), port for small vessels on the Northern coast of the Kaliningrad region (Pionerskiy) [23], a new yacht Marina in port Sochi, berths of 1A and 1B in the port of Tuapse [37].

V. Conclusions

1. Classified configurations of the port waters and approach channels from the point of view of their deposition by sediment wave field or not wave currents.

2. Defined theoretical principles and computational formulas, allowing to estimate the deposition of water area and approach channel of the port having the configuration of structures according to Fig. 1 - 3, or their combinations.

3. Developed engineering calculation methods of deposition of water areas and approach channels.

4. Developed methods were applied for calculations of deposition of water areas and approach channels to a set of ports.

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