INVESTIGATION OF SEDIMENT TRANSPORT IN WATERCOURSES TAKING INTO ACCOUNT THE EFFECTS OF WIND WAVES

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АННОТАЦИЯ.

С целью изучения транспорта наносов в водотоках с учетом воздействия ветрового волнения проведены лабораторные исследования авторов. По результатам анализа этих исследований и на основе зависимости Ван-рейна получена зависимость для определения транспорта донных наносов с учетом ветрового волнения.

ABSTRACT.

In order to study the transport of sediment in watercourses, taking into account the effects of wind waves, laboratory studies of the authors were carried out. According to the results of the analysis of these studies and on the basis of the Van-Rhein dependence, a dependence was obtained to determine the transport of sediment based on wind waves.

Ключевые слова: волна, транспорт, наносы, попутное течение, встречное течение, обрушение.

Key words: wave, transport, sediments, passing current, countercurrent, collapse.

Solving the problem of sediment transport caused by various types of wave movements plays a crucial role in studying a wide range of issues of coastal zone dynamics, as well as in identifying the role of wave factors in channel-forming processes occurring in major rivers and earthen channels. As studies carried out in recent years [6, 8] show, for large channels with straight sections several kilometers long and several soat-meters wide, the formation of wind waves of height I m is possible. These waves, spreading on the passing or oncoming flow, can have a significant impact on the general channel, transport of riverbed sediments and restructuring of the ridge topography. In this regard, the forecast of sediment transport in combined complex streams is of crucial importance for the modern design of canals and carrying out rectification works in their beds.

When analyzing the contribution of wave movements to the dynamics of river sediments, the most studied can be considered the question of the alongshore sediment transport caused by the destruction of the waves and the loss of their energy in the coastal zone of open watercourses. Despite the fact that the main specific features of this phenomenon are described quite well by modern models [3], the error in calculating the amount of material transported along coastal streams according to the methods proposed by various authors may be several times higher than the absolute value of alongshore sediment transport. One of the less studied is the question of sediment transport by surface (and primarily wind) waves in the central part of the earthen canals and on its slopes before the collapse of the waves. The data of experimental and field studies show that in these areas, under the action of wind waves, significant rearrangement of the bottom relief can be observed and they serve as additional, and sometimes the only (for example, in the presence of lining of the coast) sources of sediment inflow into the near-surface part of open water bodies and streams. The difficulties in studying the latter issue are primarily determined by the fact that, unlike the along-coast sediment transfer, the calculation of which in most cases involves the use of the energy approach, the forecast of sediment transport in the wave flow before the collapse of the waves implies the use of the most promising classical methods of hydromechanics and, first of all, the theory of the boundary layer.

Currently, the study of sediment transport in the wave flow is carried out in two directions - theoretical and experimental. The experimental studies of Bagnold [12] laid the foundation for a systematic study of the transfer of solid material under the action of waves. Further laboratory and field studies [1,5,6,14,16] expanded the understanding of the nature of unidirectional sediment transport in wave streams and showed the main factors determining this process.

Modern concepts of sediment transport in the bottom layer are associated with the asymmetry of the wave flow properties [4], which leads to the emergence of directional transfer of water masses by waves in shallow basins, was first built by Longue-Higgins [15] and brought a number of important results that were further confirmed in the conditions of the laminar mode of wave motion data of experimental studies. However, during the transition from the laminar to the turbulent regime, the empirical dependences of the wave mass transfer on the wave parameters were obtained, differing from the conditions of the laminar layer [13]. Since the relationships between the parameters of the wave flow observed in nature in most cases correspond to the conditions for the existence of a turbulent boundary layer, it becomes necessary to analyze the sediment transport in the wave flow taking into account the turbulent nature of the movement and the main features of the interaction of the flow with its eroded bed, which find their origin ridge (riffle) bottom relief of the rolling bed.

Analysis of existing methods for calculating sediment transport wave flow indicates the existence of two approaches to the prediction of sediment transport under the influence of wind waves [2]. In the first case, the formulas are matched, similar in structure to the dependencies for sediment transport in a channel stream. In the second approach, it is associated with the use of wave mass transfer and is called energy by some authors. However, both approaches have not yet led to the generally accepted method of calculation [6].

On the issue of joint transport of sediment by waves and current, there are only separate publications [17,18], which analyze the transfer of solid material under conditions of saturation of the flow with sediments. For the conditions of the clarified stream, as far as the authors of this article know, there are no calculation methods, despite the fact that this question is of great importance in analyzing the erosion ability of clarified streams when wind waves are applied to it. In this article, an attempt has been made to develop a method for calculating the transport of sediment by waves and currents for conditions of a clarified and saturated sediment stream based on laboratory studies and an analysis of current concepts of the transport capacity of channel and wave flows in large earthen channels.

As an initial analysis of sediment transport in a wave flow, the calculation method [19] is used, according to which the specific consumption of bottom sediment (q_s) in a unidirectional channel flow can be represented as:

$$q_s = 0{,}053\sqrt{gd_{cp}(S-1)}\frac{d_{cp}}{D_*^{0,3}}\left(\frac{U_{*0}^2}{U_{*kp}^2}\right)^{2,1} \qquad (1)$$

where d_{cp} is the average diameter of the bottom sediment; U_{*0}, U_{*kp} - respectively, the dynamic velocity of the channel flow and the beginning of the movement of sediment; g - gravitational acceleration; S is the relative density of bottom soil;

$$D_* = d_{cp}\left[\frac{g(S-1)}{\nu^2}\right]^{1/3} \qquad (2)$$

ν - coefficient of kinematic molecular viscosity.

To be able to use the dependence (1) in the conditions of oscillating wave motion, we represent it in a modified form:

$$q_s = a\sqrt{gd_{cp}(S-1)}\frac{d_{cp}}{D_*^{0,3}}\left(\frac{U_{*ekv}^2}{U_{*kp}^{\prime 2}}\right)^{2,1} \qquad (3)$$

where a is some empirical coefficient; $U_{*kp}^{\prime 2}$ - - critical dynamic speed of the beginning of the movement of sediment in the wave flow, which is determined in accordance with the previously conducted researchers [7]:

$$U_{*kp}^{\prime 2} = gd_{cp}(S-1)\theta'_{kp} \qquad (4)$$

U_{*ekv} - equivalent dynamic velocity, which in a general form will be considered the formula of dynamic velocity in a wave flow. The latter in accordance with [8] can be represented as:

$$\left.\begin{aligned}
U'_{*\kappa p} &= 0{,}158U_m\left(\frac{a_\delta}{K_S}\right)^{-0,154} && при\ \ 200 \prec \frac{a_\delta}{K_s};\\
U'_{*\kappa p} &= 0{,}229U_m\left(\frac{a_\delta}{K_S}\right)^{-0,222} && при\ \ 25 \prec \frac{a_\delta}{K_S} \le 200;\\
U'_{*\kappa p} &= 0{,}319U_m\left(\frac{a_\delta}{K_S}\right)^{-0,325} && при\ \ 2{,}5 \prec \frac{a_\delta}{K_S} \le 25;\\
U'_{*\kappa p} &= 0{,}373U_m\left(\frac{a_\delta}{K_S}\right)^{-0,489} && при\ \ 0{,}4 \prec \frac{a_\delta}{K_S} \le 2{,}5;\\
U'_{*\kappa p} &= 0{,}377U_m\left(\frac{a_\delta}{K_S}\right)^{-0,635} && при\ \ \frac{a_\delta}{K_S} \le 0{,}4.
\end{aligned}\right\} \qquad (5)$$

$K_S = \Delta + 2{,}5d_{cp}$; Δ – height of bottom forms; $U_m = h_b\pi/\tau \cdot sh(2\pi h_0/\lambda)$;

h_b, τ and λ - respectively, height, period and wavelength; h_0 - average depth of flow; $a_\delta = U_m\tau/2\pi$.

To obtain the expression, U_{*ekv} used experimental data [1] obtained in a wave tray with a sand bed (d = 0.67 mm) at maximum bottom velocities exceeding non-diluting values. This ensured the emergence in the "pure" wave flow of unidirectional transport of sediment, which was carried out in the form of movement of bottom riffles. As a result of the analysis, an expression for the equivalent dynamic speed is obtained:

$$\left.\begin{aligned} U^2_{*ekv} &= 0,068U^2_{*p} && \textit{при} \quad U^2_{*p} \geq 2U'^2_{*kp}\,; \\ U^2_{*ekv} &= 0,568U^2_{*p} - U'^2_{*kp} && \textit{при} \quad U^2_{*kp} \leq 2U'^2_{*kp}\,. \end{aligned}\right\} \tag{6}$$

Note that for the case of a “pure” wave flow, the value of the empirical coefficient was taken as a = 0.053. Comparison of actual and calculated by dependencies (2)-(6) specific consumption of bottom sediments is given in Tabl. I.

To calculate the transport of sediment during the imposition of will on the course, the dependence (3) was reduced to

$$q_s = a\rho_s\sqrt{gd_{cp}(S-1)}\,\frac{d}{D_*^{0,3}}\left(\frac{U^2_{*0}}{U^2_{*kp}} + \frac{U^2_{*ekv}}{U'^2_{*kp}}\right)^{2,1} \tag{7}$$

where $\mathrm{U}_{*\mathrm{kp}}$ - the critical speed of the beginning of the movement of sediment in the channel flow, determined by the Schild curve, which is approximated by dependencies:

$$U^2_{*kp} = gd_{cp}(S-1)\theta_{kp} \tag{8}$$

$$\left.\begin{aligned} \theta_{kp} &= 0,24(D_*)^{-1} && \textit{при} \quad D_* \leq 4 \\ \theta_{kp} &= 0,14(D*_i)^{-0.66} && \textit{при} \quad 4 < D_* \leq 10 \\ \theta_{kp} &= 0,04(D*_i)^{-0.1} && \textit{при} \quad 10 < D_* \leq 20 \\ \theta_{kp} &= 0,013(D*_i)^{0.29} && \textit{при} \quad 20 < D_* \leq 150 \\ \theta_{kp} &= 0,055 && \textit{при} \quad D_* > 150 \end{aligned}\right\} \tag{9}$$

Table 1

Experimental data on the determination of unit costs

№ п/п	Measured characteristics								Calculation data		
	h m	d mm	$h_в$ cm	λ m	τ s	L_p cm	Δ cm	q_s g/m·s	L/m cm/s	$U^2{}_*$ cm^2/s^2	q_s g/m·s
1	0,40	0,67	9,5	4,1	2,2	6,5	1,7	0,94	20,8	18,0	0,52
2	0,60	"	15,0	4,9	2,2	10,5	2,3	0,85	25,2	28,2	1,33
3	0,60	"	15,0	4,9	2,2	9,1	1,9	0,72	25,2	25,2	1,05
4	0,80	"	15,0	5,1	2,2	8,0	1,7	0,74	18,7	15,8	0,39
5	0,40	"	11,5	3,3	1,6	6,0	1,5	0,92	26,8	28,6	1,37
6	0,40	"	11,5	3,3	1,6	6,7	1,4	0,28	26,8	27,6	1,27
7	0,50	"	13,5	3,4	1,6	5,7	1,2	0,52	24,6	22,5	0,83
8	0,60	"	15,0	3,5	1,6	6,8	1,4	0,80	22,0	21,5	0,76
9	0,80	"	20,0	3,5	1,6	6,2	1,3	0,91	20,5	18,1	0,53
10	0,25	"	11,0	1,6	1,2	6,6	0,8	0,14	24,0	20,3	0,67
11	0,25	"	11,0	1,6	1,2	6,4	1,0	0,78	26,2	27,1	1,23
12	0,25	"	11,0	1,6	1,2	7,5	1,0	0,84	26,2	27,1	1,23
13	0,25	"	11,0	1,6	1,2	5,6	0,7	0,76	24,0	19,5	0,62
14	0,25	"	11,0	2,4	1,8	5,5	0,6	0,30	26,0	15,7	0,56
15	0,25	"	8,0	2,4	1,8	6,7	0,8	0,20	18,0	12,0	0,22
16	0,25	"	12,0	1,6	1,1	6,3	0,6	0,67	30,0	24,9	1,02

For a “pure” wave flow, $(\mathrm{U}_{*_o} = 0)$ expression (7) becomes equivalent to (3), and $(\mathrm{U}_{*\mathrm{p}} = 0)$ in the absence of waves, it coincides with expression (I). Here it is necessary to cancel that for the sediment-laden flow = 0.053.

The verification of the calculated dependence (9) for the conditions of the flow saturated with sediments (= 0.053) was carried out according to experimental data [6] obtained in a laboratory tray with sand with an average diameter of 0.67 and 2 mm. Comparison of measured and calculated by the formula (9) values of the specific consumption of bottom sediments in the combined flow are given in table 2.

Table 2

Contrast measured and calculated characteristics

Measured characteristics [6]								Calculated characteristics				
h м	V_cP м/s	d mm	$h_в$ cm	λ m	τ s	q_s g/m·s	q_s / q_{so}	Um cm/s	$U^2{}_{*/o}$ cm²/c²	$U^2{}_{*/o}$ cm²/c²	q_s g/m·s	q_s / q_{so}
0,64	0,40	0,67	20	5,8	2,1	49-77	2,37-	39,9	12,0	10,2	54	2,65
0,48	0,67	0,67	4	6,6	3,1	97	3,72	8,4	0,9	17,9	104	1,07
0,45	0,57	0,67	16	9,3	4,5	114	0,995	37,2	7,7	14,8	108	1,8
0,82	0,32	2,00	18	5,2	2,1	9,1	1,9	23,2	9,2	18,0	10	5,15
0,82	0,32	2,00	6	7,1	2,7	2,16	4,69	9,0	2,2	18,0	3,4	1,75
0,82	0,32	2,00	9	8,6	3,2	3,1-	1,11	13,8	3,5	18,0	4,38	2,26
						6,2	1,6-3,2					

It should be noted that in order to use the calculation method proposed by the authors for full-scale objects, the irregular nature of the wind waves in the conditions of large earthen channels should be taken into account. The latter is chieved by introducing the calculated values of the height, period and length of the wind waves, which are determined by the method established in [6.8].

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