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Calculation of sediment flow in channels taking into account passing and counter wind waves

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Abstract. The article discusses the process of sediment transport in channels under the influence of wind waves on the course. Based on the calculation method Quick M.C. dependences are proposed for calculating sediment transport in channels when waves are superimposed on associated and counter-current flows. The movement of sediments caused by the combined action of waves and currents is studied. It is shown that the direction of the movement of sediments is determined mainly by the direction of wave propagation (even in the case of a counter-current). Here the consumption of sediments is proportional to the power of the "wave flow" system. Comparing the results of the calculation with the dependencies of other authors gives satisfactory results.

1. Introduction

Solving the problem of deformation of channels caused by various types of non-stationary flow plays a significant role in identifying the role of non-stationary factors in bed-forming processes occurring in large ground watercourses. [1, 2, 3, 4, 5, 6].

Among the most frequently encountered non-stationary movements in riverbed flows are short wind and ship waves and their roles in the formation of stable channel beds and the transport of sediments can be considered at the present stage in the initial phase of its development [7, 8, 9].

2. Methods

The calculated wave parameters equivalent to an irregular wave for the long-range sediment flow rate are established in marine hydraulic engineering based on laboratory experiments and field measurements [10] and are as follows:

$$h_p = h_{30\%};\ T_p = \bar{T};\ \lambda_p = \bar{\lambda} \tag{1}$$

As the first approximation (1) can be taken for channel conditions. However, it should be noted that (1) is probably an overestimate for channels, since in the coastal zone of the sea, the coastal slope through the mechanisms of refraction and transformation leads to the regularization of wind waves. Besides, in the coastal zone of the sea of frequencies, there are swell waves that have a more regular character than wind waves. In the conditions of channels, these regularization mechanisms should practically not work and the sediment consumption should be less than under other equal conditions in long-distance transport [11, 12, 13]. Determine the flow rate of riverbed sediments, the power spent on the movement of sediments can be represented as [14]

$$P = \tau_0 u_T \tag{2}$$

where τ_0 is dowry shear stress; u_T is speed, determining the transport of sediments.

For the turbulent regime τ_0 proportionally u_T^3, where from,

$$P \sim u_T^3 \tag{3}$$

Speed u_T for waves on a current it is possible to represent the sum of the wave and stationary components

$$u_T = u_t + u_S \tag{4}$$

Under u_T is understand the speed averaged over the wave period.

Then

$$\overline{u}_T^3 = \overline{u}_t^3 + 3\overline{u}_t^2 u_S + 3\overline{u}_t \overline{u}_S^2 + \overline{u}_S^3 \tag{5}$$

where the top line means averaging over time over the wave period. (3) Includes the time-averaged speed.

In the second approximation of wave theory

$$u_t = u_1 \cos\frac{2\pi h}{\lambda} + u_2 \cos\frac{4\pi h}{\lambda} \tag{6}$$

where u_1, u_2 are amplitudes of the corresponding harmonics which are equal to

$$\left.\begin{aligned} u_1 &= \pi \frac{h}{T_r} sh^{-1} \frac{2\pi d}{\lambda} \\ u_2 &= \frac{3}{4} \pi \frac{h}{T_r} \pi \frac{h}{\lambda} sh^{-4} \frac{2\pi d}{\lambda} \end{aligned}\right\} \tag{7}$$

Taking into account the Doppler Effect for waves on the current allows you to convert (7) to the following form:

$$\left.\begin{aligned} u_1 &= \pi \left(\frac{h}{T_a} - \frac{hu}{\lambda} \right) sh^{-1} \frac{2\pi d}{\lambda}, \\ u_2 &= \frac{3}{4} \pi^2 \left(\frac{h}{T_a} - \frac{hu}{\lambda} \right) sh^{-4} \frac{2\pi d}{\lambda}, \end{aligned}\right\} \tag{8}$$

where T_a is the absolute period of waves (in a fixed coordinate system). Substituting (6) into (7) and averaging over time, we get

$$\overline{u}_T^3 = \frac{3}{4} u_1^2 u u_2 + \frac{3}{2} \left(u_1^2 + u_2^2 \right) u_S + u_S^3 \tag{9}$$

Then the stationary component of the flow in the bottom region is represented as:

$$u_S = k\overline{u} + u, \tag{10}$$

where $\overline{u}$ is the rate of wave-induced mass transfer. According to the well-known M. S. Longge-Higgins relationship [2]:

$$\bar{u} = \frac{5}{4}\left(\frac{\pi h}{\tau_r}\right)\left(\frac{\pi h}{\lambda}\right) sh^{-2}\frac{2\pi h}{\lambda} \tag{11}$$

For the associated flow, the bottom wave flow approximately compensates for the flow velocity defect in the bottom layer as well (Fig/1), so in this case $k = 0$.

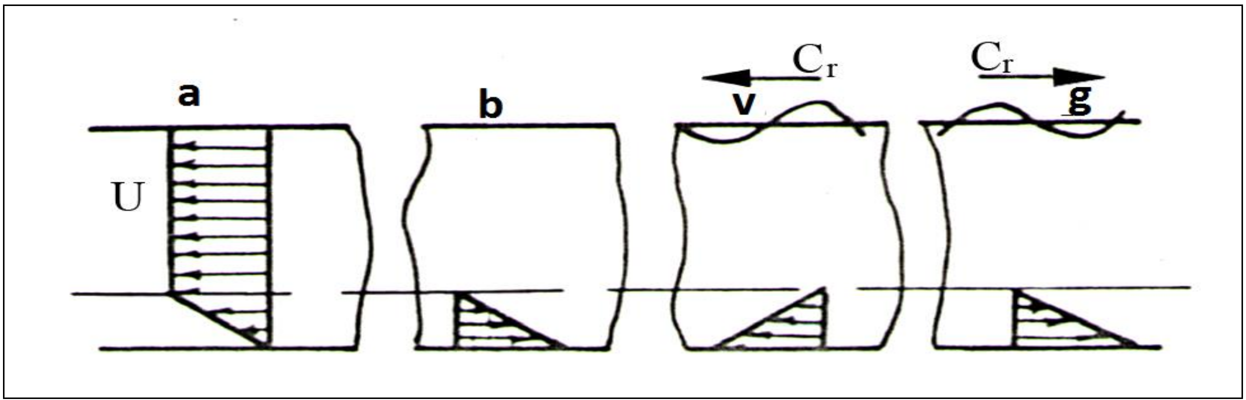

Figure 1. Diagram of the addition of the bottom wave flow and the main flow in the riverbed
a is idealized plot of the main flow velocity in a fixed coordinate system; b is plot of the main flow velocity in the relative coordinate system

Dowry wave flow. If the counter current is so significant that it causes waves to collapse, then the bottom wave current changes direction again. Finally, if only motion without flow is considered, then $k = 1$.

Since the question of the collapse of waves on the opposite current is studied very poorly and there are no even empirical criteria for determining such a collapse, it is recommended to use the well-known Misha criterion of the maximum steepness of the wave for this purpose

$$\left(\frac{h}{\lambda}\right)_{kp} = 0.142 th\frac{2\pi d}{\lambda} \tag{12}$$

Thus, for the oncoming flow in the region before the collapse of the waves, the following dependence is obtained for the stationary bottom velocity:

$$\frac{u_S}{u} = 2.5\pi^2\left(\frac{h}{uT_a} + \frac{h}{\lambda}\right)\left(\frac{h}{\lambda}\right) sh^{-2}\frac{2\pi d}{\lambda} - 1 \tag{13}$$

3. Results

Since the voltage of the total bottom velocity determines the direction of the sediment flow, in the formula (9), always in the direction of the waves. The directions of the velocity components set by the second and third terms (9) always coincide with the direction u_S that is on a collision course in the region before the collapse of waves possible sediment transport in the direction of flow towards the waves and the direction of the waves against the current. Assuming that the total flow of sediment is proportional to the transporting capacity, we obtain the dependence of the formula (3) and (9), which determines the volume of sediment qs, moved in a unit of time through a unit of channel width:

$$q_S = \frac{K}{g}\left[\frac{3}{4}u_1^2 u_2 + \frac{3}{2}(u_1^2 + u_2^2)u_S + u_S^3\right] \tag{14}$$

Where K is the coefficient of proportionality. Also, the study conducted [14] with sand with an average diameter of 0.36 mm, showed that the coefficient value is weakly dependent on the parameters of waves and flow. This conclusion is also confirmed by the data of the authors ' experiments performed with sand with a size of 0.67 mm and 2 mm [15 and 16]. The dependency (14) using the expression (8) can be represented in the following dimensionless form:

$$\frac{q_S g}{q_0} = K\frac{9}{16}\pi 4\left(\frac{h}{uT_a} \mp \frac{h}{\lambda}\right)^3 \left(\frac{h}{\lambda}\right) sh^{-6}\frac{2\pi h}{\lambda} + \\ +\frac{3}{2}\frac{u_S}{u}\pi^2\left(\frac{h}{uT_a} \mp \frac{h}{\lambda}\right)^2 sh^{-2}\frac{2\pi d}{\lambda}\left[1+\frac{9}{16}\pi^2\left(\frac{h}{\lambda}\right)sh^{-6}\frac{2\pi d}{\lambda}\right] + \left(\frac{u_S}{u}\right)^3 \quad (15)$$

The + (plus) sign corresponds to a passing current, and the – (minus) sign corresponds to an oncoming current. Formula (15) is used in conjunction with the formula (13) to calculate the flow rate of sediment in the oncoming flow in the area before the collapse of the waves. For a passing current and a counter-current after the collapse of waves in formulas (13) and (15) $u_S / u = 1$.

In [14], the results of laboratory experiments to determine the flow rate of sand sediments by waves and currents are presented. The flow rate of sediment is determined by the speed of movement of riffles formed by waves and current q_S. For figure 2 the dependence is shown according to experimental data q_S from the transporting power P, determined by the right part of the formula (14). Analysis of Figure.2 allows us to conclude that the coefficient K in (14) does not depend on the parameters of the waves and the flow and is lost for the passing current, the counter current (before and after the collapse), only the waves and only the flow. This conclusion is confirmed with satisfactory accuracy by experimental data [17, 18, 19].

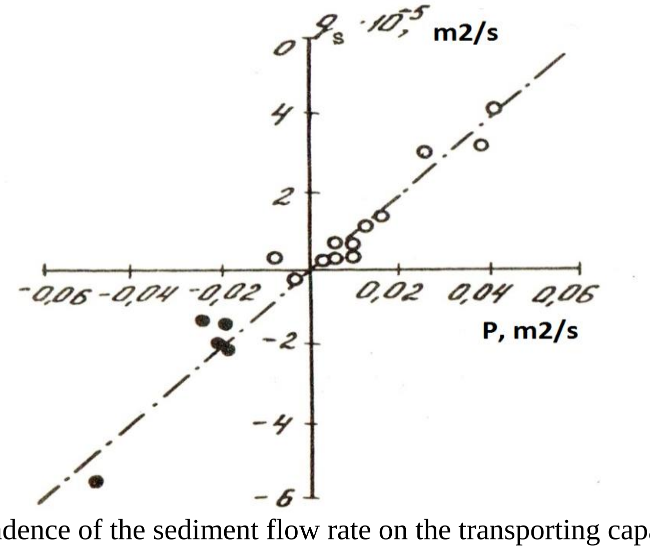

Figure.2. Dependence of the sediment flow rate on the transporting capacity in [14]:
o – experiments for the flow of waves and waves on a passing and oncoming current without collapse;
• - Experiments with the collapse of waves on the opposite current.

If there are no waves for the case of only flow from expression (15), we get

$$q_{S0} = \frac{Ku^3}{g} \tag{16}$$

4. Discussion

The formula (16) corresponds to the existing dependencies for the flow rate of riverbed sediments, in which, with fixed particle mobility and channel resistance, the flow rate of sediment is proportional to the cube of the flow rate [1]. Comparing the expression (16) with one of the most reasonable formulas for the flow rate of riverbed sediments [1] – by the formula of the graph-Askaroglu, we get

$$K = 10.4 \frac{1}{C^2} \frac{\vartheta_*^2}{\left(\frac{\rho_s}{\rho} - 1\right)^2 D} \frac{\sqrt{g}}{C} \tag{17}$$

where C is Chezy's constant; ϑ_* is dynamic speed; ρ_s is the density of the sediment; ρ is the density of water; D is the average diameter of the sediment.

5. Conclusions

Indeed, the estimate of K according to the formula (17) for the experimental conditions [8] gives $K = 1.24 \cdot 10^{-3}$ whereas from Figure 2. $K = 1.0 \cdot 10^{-3}$. In the future, it is advisable to perform similar experiments with other values of the parameters D, C and ϑ_*, which will allow us to fully verify the described method for calculating the sediment consumption. If the sediment flow rate in the case of flow only $q_{S,0}$ measured or calculated in any reliable way, the change in flow rate due to the imposition of passing or counter waves is determined by the dependence, which is obtained by dividing (15) by (16):

$$\frac{q_S}{q_{S0}} = \frac{9}{16}\pi^4 \left(\frac{h_p}{uT_a} \mp \frac{h_p}{\bar{\lambda}}\right)^3 \left(\frac{h_p}{\bar{\lambda}}\right) sh^{-6} \frac{2\pi d}{\bar{\lambda}} + $$
$$+ \frac{3}{2}\frac{u_S}{u}\pi^2 \left(\frac{h_p}{uT_a} \mp \frac{h_p}{\bar{\lambda}}\right)^2 sh^{-2} \frac{2\pi d}{\bar{\lambda}} \left[1 + \frac{9}{16}\pi^2 \left(\frac{h_p}{\bar{\lambda}}\right) sh^{-6} \frac{2\pi d}{\bar{\lambda}}\right] + \left(\frac{u_S}{u}\right)^3 \tag{18}$$

This eliminates errors in the calculation of K according to the formula (17). Thus, the above dependencies can be used to calculate the flow rate of sediment in the channel, taking into account wind waves [20]. The proposed calculation dependence is based on existing theoretical and experimental studies of domestic and foreign authors.

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