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Generation of Wind Waves in Large Streams

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Abstract--- *There are methods for calculating the waveforms in the reservoirs, taking into account the direct flow and the reverse direction of the flow and the limited acceleration due to the coasts.*

Keywords--- *Wind Waves, Effective Acceleration, Channels, Speed, Passing Currents, Oncoming Currents.*

I. INTRODUCTION

Additional factors that determine the generation of wind waves on large watercourses (flowing reservoirs, large rivers, large canals) compared to the open sea, are the current and limited acceleration of the banks. The combined effect of both factors was studied in [1, 2, 3, 4, 6, 7, 8, 10]. We make a brief review of the relevant theory, which is the basis of the method for calculating the formation of wind waves on watercourses.

Main part

For wind waves on a large-scale current, the main dynamic equation is the equation of conservation of wave action, which, as applied to the problem in question, can be written as**:**

$$\frac{\partial N}{\partial t} + \vec{r}\,\frac{\partial N}{\partial \vec{r}} + \vec{k}\,\frac{\partial N}{\partial \vec{k}} = Q_{ucm}\,, \qquad (1)$$

Where:

$$\mathrm{N}\left(\vec{\mathrm{r}}, \vec{\mathrm{k}}, \mathrm{t}\right) = S\left(\vec{r}, \vec{k}, t\right) / \omega_r \qquad (2)$$

Wave spectral density, $S\left(\vec{r}, \vec{k}, t\right)$- spatial amplitude spectrum of waves, ω_r – frequency, corresponding to the spectral component $\vec{k}\left(k_x, k_y\right)$ at the point $\vec{r}(x, y)$ at time t in the reference frame moving with the flow velocity $\vec{U}(\vec{r}, t)$. The principle of conservation of wave action is valid for waves in a moving medium, was established by Bretherton, Garret in 1969 [9] and is developed for waves on water by Weisem.

In the one-dimensional case, equation (1.1) is simplified as follows:

$$\frac{\partial N}{\partial t} + \frac{\partial x}{\partial t}\frac{\partial N}{\partial x} + \frac{\partial k}{\partial t}\frac{\partial N}{\partial \vec{k}} = Q_{ucm}\,. \qquad (3)$$

Characteristics of the equation (3):

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$$\begin{aligned}\frac{\partial x}{\partial t}=\frac{\partial \omega}{\partial k}=C_{ga}\\ \frac{\partial k}{\partial t}=\frac{\partial \omega}{\partial x}=0\end{aligned}, \qquad (4)$$

where C_{ga} – absolute group speed, $C_{ga}=C_{gr}+U$. In accordance with (3) and (4) the condition on the characteristics is:

$$\frac{\partial N}{\partial t}+C_{ga}\frac{\partial N}{\partial x}=Q_{ucm}. \qquad (5)$$

In the steady state, when sufficient time is reached, the wave action ceases to depend on time, and is only a function of the run. In this case, equation (1.5) takes a very simple form:

$$C_{ga}\frac{\partial N}{\partial x}=Q_{ucm}. \qquad (6)$$

Consequently, using the method of characteristics and separating the variables in equation (6), we can write the solution of equation (3) in the following implicit form:

$$\int_{N_0}^{N}\frac{dN}{Q_{ucm}}=\int_{\mathrm{x}_0}^{\mathrm{x}}\frac{\mathrm{dx}}{\mathrm{C}_{\mathrm{ga}}}, \qquad (7)$$

where

$$N=N_0\big|_{x=x_0} \qquad (8)$$

is a boundary condition. Since the group velocity at constant depth and flow velocity does not depend on the coordinate, the right-hand side of equation (7) is reduced to the form:

$$\int_{\mathrm{x}_0}^{\mathrm{x}}\frac{\mathrm{dx}}{\mathrm{C}_{\mathrm{ga}}}=t-t_0=\frac{x-x_0}{C_{ga}}, \qquad (9)$$

where t-t_0 – wave propagation time with group velocity from the boundary point. From (7) and (9) it follows that the following transformation of the coordinate (on $x_0=0$)

$$\frac{x}{C_{ga}}=\frac{X}{C_{g0}}\ \textit{или}\ \frac{\mathrm{X}}{\mathrm{x}}=\frac{C_{g0}}{C_{ga}} \qquad (10)$$

where C_{g0} – group speed on still water, gives a distance of run-up x over the amount of wave action $N(x)$, equal to $N_0(X)$ – the magnitude of the wave action on the length of the run X on still water. Thus, relation (10) determines the effective acceleration length for wind waves in a current.

Determination of the effective acceleration length for waves in a current is considered in more detail in [6], where, in particular, it is shown that if the angle between the wind and current vectors is α, then the effective acceleration length is determined by the ratio:

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$$\frac{\mathrm{X}}{\mathrm{x}} = \frac{C_{g0}}{C_{gr} + U\cos\alpha}, \qquad (11)$$

Where C $_{gr}$ – group velocity of waves in the coordinate system associated with the flow.

The concept of effective acceleration length for waves in a current gives the correct qualitative tendency of the influence of a current on the development of waves.

Indeed, in deep water $C_{ga} = C_{g0} + U$ and on the way (*U>0*) from (1.10) follows that *X/x<1*, those effective length of acceleration is less than the actual. On the contrary, on a counter course (*U<0*) from (1.10) follows that *X/x>1*, the effective acceleration length is greater than the actual geometric length. Such a flow effect corresponds to the data obtained in aerohydrodynamic channels [11–13], where the wind waves on the tail current are less, and on the oncoming flow more than in the absence of the flow, all other conditions being equal.

The effective acceleration length can be determined from equation (11), in which the relative group velocity must be specified. For this, an experimental dependence can be used for the frequency of the maximum of the wave spectrum in the coordinate system of the flow [13]:

$$\frac{u_* f_{pr}}{g} = 0{,}939\left(\frac{gX}{u_*^2}\right)^{-0{,}354} \qquad (12)$$

Where u_* - wind friction velocity in a fixed coordinate system. If we go in the relation (12) to the wind speed and the average frequency in the spectrum using the following relations [14]:

$$W = 25u_* \quad \bar{f} = 1{,}17 f_p, \qquad (13)$$

Then the expression (12) takes the form:

$$\frac{\overline{\omega}_r W}{g} = 14{,}28\left(\frac{gX}{u_*^2}\right)^{-0{,}354}, \qquad (14)$$

Where ω_r – average relative circular frequency. Then for the average group velocity we get:

$$\overline{C}_{gr} = \frac{0{,}44W}{4\pi}\left(\frac{gX}{u_*^2}\right)^{-0{,}354}. \qquad (15)$$

And for the effective acceleration length, the following implicit equation is obtained from relation (11):

$$\frac{X}{x} = \frac{1}{\left(\frac{X}{x}\right)^{0{,}354} + \frac{4\pi}{0{,}44}\frac{U\cos\alpha}{W}\left(\frac{gx}{W^2}\right)^{-0{,}354}}. \qquad (16)$$

The numerical solution of equation (1.16) is shown in Figure 1.1. In Figure 1.1, the decision refers to the co-current, when $U\cos\alpha/W > 0$ и *X/x<1*. Figure 1.1b shows a solution for a counter flow: $U\cos\alpha/W < 0$ и

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X/x>1. The curves in Figure 1.1 clearly demonstrate how important the flow factor can be, which can increase or decrease the acceleration length, especially at limited acceleration lengths.

The introduction of an effective length of acceleration allows the use of the following GOIN-SoyuzMorNIIproekt formula [5] for calculating the average height and period of the waves over a current:

$$\frac{g\overline{H}}{W^2} = 0{,}16\left\{1-\left[\frac{1}{1+6{,}0\times10^{-3}\left(gX/W^2\right)^{0{,}5}}\right]^2\right\} th\left\{0{,}625\frac{\left(gd/W^2\right)^{0{,}8}}{1-\left[\frac{1}{1+6{,}0\times10^{-3}\left(gX/W^2\right)^{0{,}5}}\right]}\right\}, \quad (17)$$

$$\frac{g\overline{T}_r}{W} = 3{,}1\times 2\pi\left(\frac{g\overline{H}}{W^2}\right)^{0{,}625}$$

Where T_r – the period of the waves in the moving coordinate system (in the flow system), d – water depth at acceleration. As shown in [5], the dependences (17) are consistent for the case of the absence of a flow with a large amount of data of natural wave measurements.

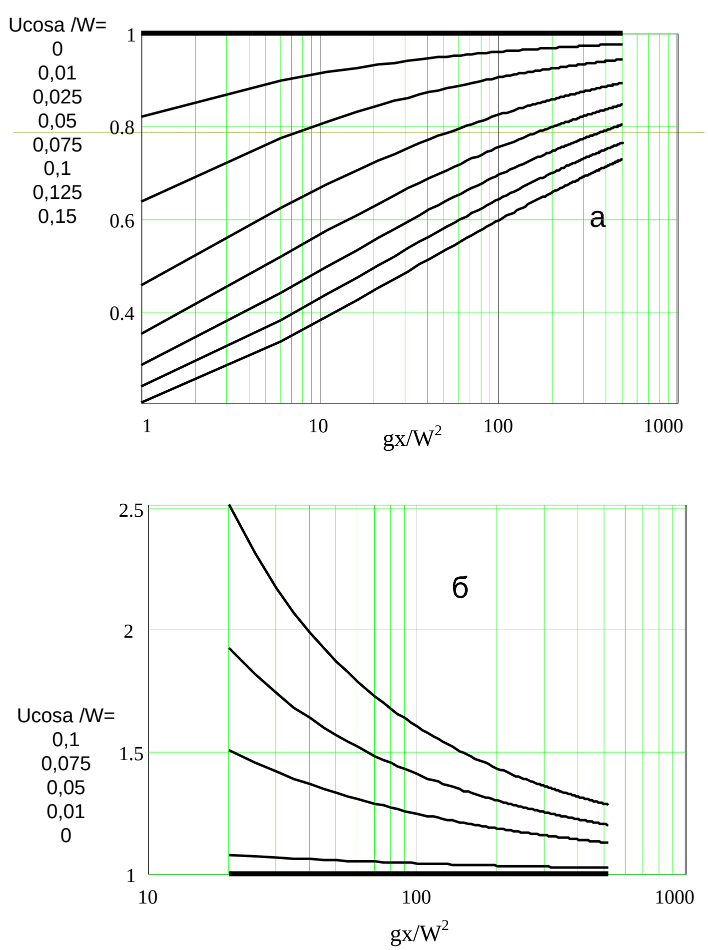

Fig.1.1: The dimensionless acceleration length for wind waves during:

a) on the course, b) on the opposite

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When forecasting wind waves in limited water areas (large rivers, canals, reservoirs, coastal zone of the sea), it is necessary to take into account the limitation of acceleration by the coastline. This factor in conditions of narrowness or complex configuration of the coastline may be no less important than the flow.

The principle of taking into account the influence of the coastline on the limitation of acceleration is known. For the coastal zone of the sea, the corresponding techniques are given in [15]. For estuaries, straits and channels that can be approximated in terms of a rectangle, the method of taking into account the limited width of the channel is given in [16].

It also uses the effective acceleration length, which we will call effective overclocking limiting. The latter value is determined by integrating the acceleration lengths, measured from the calculated point to the intersection with the coastline, by the angle between the local and general wind speed directions:

$$\frac{F}{x} = \int_{-\theta'}^{\theta'} p(\theta)x(\theta)d\theta \Bigg/ \int_{-\theta'}^{\theta'} xd\theta \quad , \qquad (18)$$

where θ' – a raster of corners of the effective wave-forming effect of the wind, $p(\theta)$ – weight function.

The raster of effective wave formation is assumed to be 90 degrees to both sides of the general direction for a complex outline of the coastline and from 30 to 90 degrees in the case of watercourses. The type of weight function depends on the distribution of wind speed in directions and on local conditions. So with $\theta'=30^0$ and $p(\theta)=1$ the solution often used for channels is obtained:

$$\frac{F}{x} = \frac{6}{\pi}\left[\ln tg\left(\frac{1}{2} arctg\,\frac{b}{2x} + \frac{\pi}{4}\right) - 1{,}317\frac{b}{2x} - \frac{b}{2x}\ln tg\left(\frac{1}{2} arctg\,\frac{b}{2x}\right)\right], \qquad (19)$$

where b – channel width. The type of function (1.19) is shown in fig. 1.2.

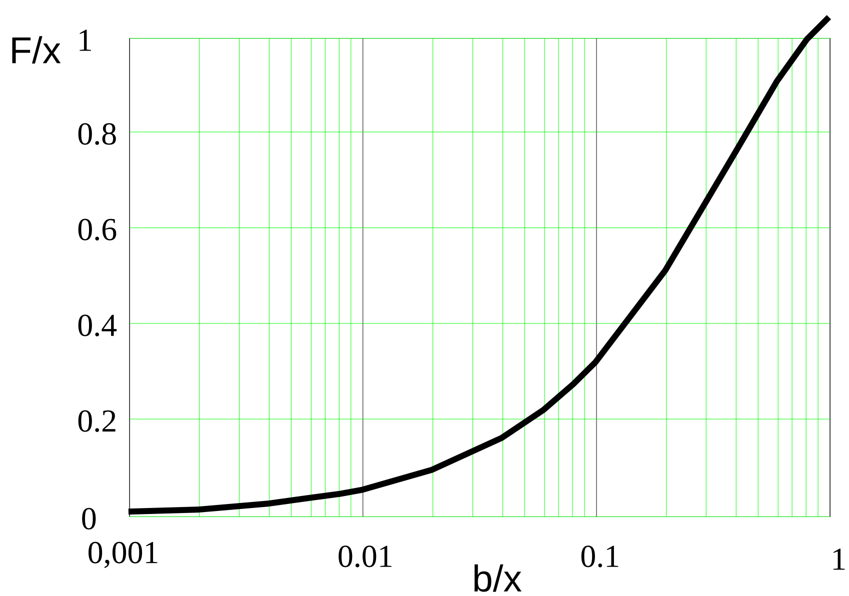

Fig.1.2: The influence of the relative width of the channel on the acceleration of waves

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The calculation method, which takes into account the influence of both the current and the complex configuration of the coastline, is as follows and is used further to calculate the size of wind waves in the region of the transition under study. The principles of the methodology are detailed in [7, 8].

The algorithm represents a generalization of the method for calculating wind waves with a complex configuration of the coastline. From the calculated point with an interval of 22,5 degrees to both sides of the main beam with the number *n=1* spend extra rays with numbers $n = \pm 2, \pm 3, \pm 4$. Then, for each beam, the effective acceleration length with the flow is determined:

$$X(\alpha) = \Delta \sum_{i=1}^{n} \left(\frac{X}{x} \right)_i , \tag{20}$$

where Δ - length of the calculated area, $(X/x)_i$ determined by the formula (16), in which the corresponding projection of the flow velocity is involved. The beam continues to the intersection with the line of the coast. In the case of relatively small accelerations, we can neglect the curvature of the wave beam and use the relation (20) for the entire beam.

Further, for each wave beam, the first wavelength is calculated using the first formula (17), the average wave height for the studied water area is determined by weighted averaging in accordance with the recommendations [13]:

$$\overline{H} = 0{,}1\left\{25\overline{H}_1^2 + 21\left(\overline{H}_2^2 + \overline{H}_{-2}^2\right) + 13\left(\overline{H}_3^2 + \overline{H}_{-3}^2\right) + 3{,}5\left(\overline{H}_4^2 + \overline{H}_{-4}^2\right)\right\}^{\frac{1}{2}} . \tag{21}$$

Then, by the second of formulas (17), the average period of the waves is determined.

For the transition from the average height and period of the waves to the height and period of a given security in the system, the distribution function of the heights of the wind waves in the form of the Rayleigh distribution is used, which is assumed to be fair and for effective acceleration. In particular, the following relations can be applied to determine the height and period of significant waves:

$$\overline{H} = 0{,}625 H_s \quad \overline{T} = 0{,}9 T_s . \tag{22}$$

As measurements show, there is a feature for the countercurrent that relates to the initial part of the acceleration. In this area, the wind waves generated propagate downstream, and downwind, i.e. upstream spread wave groups. It is natural to assume that for a given wave the length of the initial segment is determined by the relation:

$$C_{gr} = U\left|\cos\alpha\right| , \tag{23}$$

What, using the expression (1.15) for group velocity, can be written in the form:

$$\left(\frac{X}{x}\right)^{0,354} - \frac{4\pi}{0{,}44}\frac{U}{W}\left(\frac{gx}{W^2}\right)^{-0,354}\left|\cos\alpha\right| = 0 . \tag{24}$$

If we solve for the beam on a counter-current of equation (24) and (16) together, then we can take into account the effect of the initial segment.

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The developed technique was confirmed by field measurements made by the authors on the Kara Kum Canal, as well as SANIIRI measurement data on several Central Asian channels [6]. For an idea of the ranges of the performed comparison, the measurements of the authors, together with the data of the calculations, are presented in Table 1.1.

Table 1: Comparison of the results of the calculation of wind wave heights with measurement data

Acceleration length, m	Channel width, m	Water depth, m	Wind speed, m / s	Flow rate, m / s	Average wave height, cm	
					Measurements	Calculation
256	134	4,6	5,3	-0,42	4,5	4,3
258	134	4,6	6,9	-0,42	5,8	6,7
258	134	4,6	4,1	-0,42	3,3	3,0
795	167	3,8	5,7	0,42	6,0	6,1
795	167	3,8	5,8	0,42	6,3	6,2
137	55	3,2	9,4	-0,55	8,0	5,8
198	55	3,2	6,1	-0,55	5,6	3,7
180	50	2,1	15,8	-0,53	14,0	14,0
125	50	2,1	17,2	-0,53	13,0	11,0
180	50	2,1	6,0	-0,53	1,6	1,5

From the table it can be seen that a comparison of the results of the calculation of the height of wind waves with the measurement data gives a good ratio.

II. Conclusion

In conclusion, we can conclude that when calculating the formation of wind waves along the current in flowing reservoirs, large and small rivers, and large canals, we can use the proposed calculation method.

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