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Model for calculating the hydraulic parameters of channels with a dynamically stable section

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Abstract. In today's climate change conditions, it is difficult to imagine agriculture as separate from irrigated agriculture. When taking water from the river, transferring a large number of river sediments along with water to crop fields through irrigation networks requires high carrying capacity and resistance to deformation from irrigation channels. In this process, correct assessment of the factors affecting the sedimentation of the flow and ensuring that the velocity in the channel is at the limit values determines the dynamic strength of the channels. In the paper, based on the analysis of some models representing suspended turbulent flow motion and a new generalized mathematical model based on the theory of interfering media, the equation for calculating the relative width of the channel (β) for two-phase turbulent flow containing suspended sediments and the interaction of the riverbed is taken into account. It was found that the results of this equation were very close to the results of field studies compared to existing computational methods compared with the values of field studies conducted on dynamically stable section channels and the values calculated by existing computational methods.

1 Introduction

Modern irrigation practice is associated with feeding the channels with river water, which carries a significant amount of suspended sediments that partly enter the channel. Under these conditions, stable channel cross-sections are formed in such a way that sediment transport is ensured [1]. Thus, the formation of stable channels is in direct connection with the sediment regime, the sedimentation of the flow with a certain amount of suspended sediments is an important and, often, a determining factor for the course of the channel process and the formation of certain shapes and sizes of channels [2].

In the modern concept of the channel process, as the interaction of a flow with a deformable channel, we mean the interchange of the flow and the channel by sediment. The main active factor of such interchange of sediments is the averaged velocity and the turbulent structure of the flow, which depend on the morphometry and roughness of the channel. [3]. In the interchange of sediments, there is constant sedimentation of suspended

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sediments and a compensating process - the erosion of settled suspended sediments and the involvement of temporarily immobile sediment particles in the movement. When a stable channel is formed under the influence of the channel process, the process of such exchange is balanced; there are no unidirectional deformations, and the channel is in a stable state. From this, it follows that in stable channels, the velocity structure of the flow across the width of the section is in dynamic correspondence with the shape of the channel. Such channels are called dynamically stable [4]. Thus, it turns out that dynamically stable channel sections are determined by a combination of several factors, the main ones of which are: the relationship between the flow velocity structure and the channel shape, at which there is a certain velocity distribution over the entire channel cross section; quantitative in the fractional composition of all categories of the soil of the bed of clay fractions, which change the physical and mechanical properties of the soil; turbidity of the flow, suppressing the turbulence of the flow in the natural area and changing the roughness of the bed, which creates conditions for increasing the permissible speed for erosion [5,6].

All these factors are currently not yet reflected in theoretical dependencies; therefore, an indirect method has been widely developed when the characteristics of stable channels are determined according to the data of field studies. Such scientific directions are widely developed in the CIS countries, the USA, France, and India, the dependences determining the stable shape and size of the channels are established based on statistical processing of observation materials on the operated channels, operating in a stable mode, without erosion and siltation [7]. It turns out that the known dependencies for constructing dynamically stable sections of channels are empirical, which narrows their field of application.

2 Materials and Methods

To develop this direction, we will consider the equations of motion of a suspended flow in open channels [8,9].

In the case of a steady-state uniform motion of a two-phase fluidity, the equations of motion of a turbulent flow, according to what we obtain [10-12].

$$\begin{cases} \frac{\partial}{\partial y}\left(f_1\mu_1\frac{\partial u_1}{\partial y}\right)+\frac{\partial}{\partial z}\left(f_1\mu_1\frac{\partial u_1}{\partial z}\right)+K(u_2-u_1)-L_1u_1=-f_1\rho gi \\ \frac{\partial}{\partial y}\left(f_2\mu_2\frac{\partial u_2}{\partial y}\right)+\frac{\partial}{\partial z}\left(f_2\mu_2\frac{\partial u_2}{\partial z}\right)+K(u_2-u_1)-L_2u_2=-f_2\rho gi \end{cases} \tag{1}$$

In this case, if we take into account that the concentration of the second phase is very small, $f_1 = 1$ and $u_2 = u_1$, then the first equation of the last system can be taken as in the single-phase case

$$\mu_1\frac{\partial^2 u_1}{\partial y^2}+\mu_2\frac{\partial^2 u_1}{\partial z^2}-L_1u_1=-\rho gi \tag{2}$$

The solution to equation (2) is given [10], where the hydraulic parameters are determined from the condition of equilibrium of the friction force on the contour of the channel section

$$f_1\mu_1\frac{\partial u_1}{\partial y}\bigg|s+f_2\mu_2\frac{\partial u_2}{\partial y}\bigg|s+f_1\mu_1\frac{\partial u_1}{\partial z}\bigg|s+f_2\mu_2\frac{\partial u_2}{\partial z}\bigg|s=\tau_0 \tag{3}$$

taking into account that $u_1 = u_2$ we obtain that

$$\sqrt{\frac{L_2}{\mu_2}}(f_1\mu_1+f_2\mu_2)\left(\frac{sh\sqrt{\frac{L_2}{\mu_2}}y}{ch\sqrt{\frac{L_2}{\mu_2}}a-1}\right)\Bigg|_{\chi}+\sqrt{\frac{L_2}{\mu_2}}(f_1\mu_1+f_2\mu_2)\left(\frac{sh\sqrt{\frac{L_2}{\mu_2}}}{ch\sqrt{\frac{L_2}{\mu_2}}b-1}\right)\Bigg|_{\chi}=\tau_0. \tag{4}$$

Then at the extreme upper points of the channel, we have

$$\sqrt{\frac{L_2}{\mu_2}}(f_1\mu_1+f_2\mu_2)\frac{sh\sqrt{\frac{L_2}{\mu_2}}a}{ch\sqrt{\frac{L_2}{\mu_2}}a-1}=\tau_0 \tag{5}$$

and at the lower point of the channel section

$$\sqrt{\frac{L_2}{\mu_2}}(f_1\mu_1+f_2\mu_2)\frac{sh\sqrt{\frac{L_2}{\mu_2}}b}{ch\sqrt{\frac{L_2}{\mu_2}}b-1}=\tau_0 \tag{6}$$

where τ_0 is expresses the value of the friction force on the contour of the channel section, which is assumed to be a constant value.

Then, system (1) expresses the dependence for determining the values of *h* and *b.* It is easy to guess that to determine the relationship between *h* and *b* from (1), you can get

$$\sqrt{\frac{L_2}{\mu_2}}\frac{\rho gi}{L_2}(f_1\mu_1+f_2\mu_2)\frac{sh\sqrt{\frac{L_2}{\mu_2}}a}{ch\sqrt{\frac{L_2}{\mu_2}}a-1}=\sqrt{\frac{L_2}{\mu_2}}\frac{\rho gi}{L_2}(f_1\mu_1+f_2\mu_2)\frac{sh\sqrt{\frac{L_2}{\mu_2}}b}{ch\sqrt{\frac{L_2}{\mu_2}}b-1} \tag{7}$$

If we take into account the erosion of the channel, the equilibrium equation on the contour of the channel section can be represented as

$$\sqrt{\frac{L_2}{\mu_2}}\frac{\rho gi}{L_2}(f_1\mu_1+f_2\mu_2)\frac{\partial U}{\partial y}\bigg|_{\chi}+\sqrt{\frac{L_2}{\mu_2}}\frac{\rho gi}{L_2}(f_1\mu_1+f_2\mu_2)\frac{\partial U}{\partial z}\bigg|_{\chi}=\tau_0+qL_2\frac{f}{\sqrt{1+\left(\frac{dy}{dz}\right)^2}} \tag{8}$$

where: f is sliding friction coefficient of channel particles; q is elementary water consumption,$q=\frac{Q}{b},{}^{m^2}/_{sek}$

Using the equation of the channel section shape and for $\alpha=\sqrt{\frac{L_2}{\mu_2}}$ [8], we obtain

$$\alpha\frac{\rho gi}{L_2}(f_1\mu_1+f_2\mu_2)\frac{ch\alpha y-1}{ch\alpha b-1}+\alpha\frac{\rho gi}{L_2}(f_1\mu_1+f_2\mu_2)\frac{ch\alpha z-1}{ch\alpha h-1}=1. \tag{9}$$

From here:

$$\frac{ch\alpha y-1}{ch\alpha b-1}+\frac{ch\alpha z-1}{ch\alpha h-1}=\frac{L_2}{\alpha\rho gi(f_1\mu_1+f_2\mu_2)}. \tag{10}$$

Then the equation of the channel section shape takes the following form:

$$y=\frac{1}{\alpha}arcch\left(\left(\frac{1}{\alpha\rho gi(f_1\mu_1+f_2\mu_2)}-\frac{ch\alpha z-1}{ch\alpha h-1}\right)\times(ch\alpha b-1)+1\right) \tag{11}$$

For $A=\frac{L_2}{\alpha\rho gi(f_1\mu_1+f_2\mu_2)}$, we assume that for specific conditions, the value of A is assumed to be constant.

Then, in a more simplified form for the shape of the channel section, we have:

$$y=\frac{1}{\alpha}arcch\left(\left(A-\frac{ch\alpha z-1}{ch\alpha h-1}\right)\times(ch\alpha b-1)+1\right). \tag{12}$$

Now, from the equilibrium condition on the contour of the section χ, we determine the value, h is the depth of the flow, and b is the width of the flow along the top:

$$\alpha\frac{\rho gi}{L_2}(f_1\mu_1+f_2\mu_2)\left.\frac{\partial u}{\partial y}\right|_\chi+\alpha\frac{\rho gi}{L_2}(f_1\mu_1+f_2\mu_2)\left.\frac{\partial u}{\partial z}\right|_\chi=\tau_0+\frac{qL_2f}{\sqrt{1+\left(\frac{dy}{dz}\right)^2}} \tag{13}$$

Using the equation of a sectional shape of the channel (2), we obtain the following:

$$\alpha\frac{\rho_2 gi}{L_2}(f_1\mu_1+f_2\mu_2)\left.\left(\frac{sh\alpha y}{ch\alpha b-1}\right)\right|_\chi+\alpha\frac{\rho gi}{L_2}(f_1\mu_1+f_2\mu_2)\left.\left(\frac{sh\alpha}{ch\alpha h-1}\right)\right|_\chi=\tau_0+\frac{qL_2f}{\sqrt{1+\left(\frac{dy}{dz}\right)^2}} \tag{14}$$

Then for small values $\sqrt{1+\left(\frac{dy}{dz}\right)^2}\approx 1$ at the upper points of the channel, we have:

$$\alpha\frac{\rho_2 gi}{L_2}(f_1\mu_1+f_2\mu_2)\frac{ch\alpha h}{ch\alpha h-1}=\tau_0 \tag{15}$$

At the lower point of the section concerning (1), respectively, we obtain:

$$\alpha\frac{\rho_2 gi}{L_2}(f_1\mu_1+f_2\mu_2)\frac{ch\alpha b}{ch\alpha b-1}=\tau_0+\frac{QLf}{B}. \tag{16}$$

The hydraulic elements of the proposed dynamically stable channel section h (channel depth) and b (channel width) are determined depending on (15) and (16).

Hence, at $\frac{ch\alpha b}{ch\alpha b-1}\approx 1$, to determine the width along the water's edge for a dynamically stable channel, we obtain the following dependence [13-16]:

$$B = \frac{QfL_2}{\alpha\rho gi(f_1\mu_1 + f_2\mu_2) - \tau_{доп}L_2}. \tag{17}$$

where B is channel width along the water's edge; L_2 is coefficients, turbulence factor ; g is acceleration of gravity, m/sec^2; $\tau_{доп}$ is permissible shear stress, N/m^2; f_1, f_2 are phase concentrations; μ_1, μ_2 are dynamic viscosity coefficients of the carrier and carrier phases, Ns/m^2.

3 Results and Discussion

For channels fed with more clarified water from reservoirs or rivers with low sediment content (with data saturation and suspended sediment $\varepsilon < 0.5\ kg/m^3$), for given $Q,\ \tau_{dop}$, $n,\ b\ and\ i$, the relative channel width is recommended to be determined from the dependence obtained from (17):

$$\beta = \frac{B}{h} = \frac{QfL_2^2}{\tau_{dop}(\alpha - L_2)} \tag{18}$$

The calculation can be carried out on a computer in the DELPHI language [14]. The use of computing programs greatly simplifies the computation process.

Table 1. Comparison of the results of the proposed method with the results of other authors.

Channel name	Q, m^3/sec	The relative width of the channel, b/h				
		according to S. Altunin	according to A. Girshkan	according to K. Rabkova	measured	recommend
Tashkent	74	11.7	10.3	10.2	7.5	9.7
Handam	10	12.8	6.8	6.8	6.4	6.5
Parkent	26	34.7	7.5	7.5	9.5	9.2
Big Andizhan	100	24.9	9.5	10.9	11.3	10.1
Big Ferghana	36	17.7	9.1	8.8	11.5	12.0
Mirishkor	100	22.0	13.2	11.5	11.5	10.6
Kegeyli	140	12.7	11.8	11.6	13.0	12.8
Kuvanysh-jarma	185	26.9	12.6	12.3	14.2	13.8
Suenli	130	25.8	11.3	11.4	10.0	10.3
Parallel	140	26.0	11.5	11.6	9.9	10.1
Qizketgen	400	19.0	15.4	14.3	18.4	18.3

The calculation results were compared with the full-scale data of the channels and by the dependences of different authors for the conditions under consideration (Table 1).

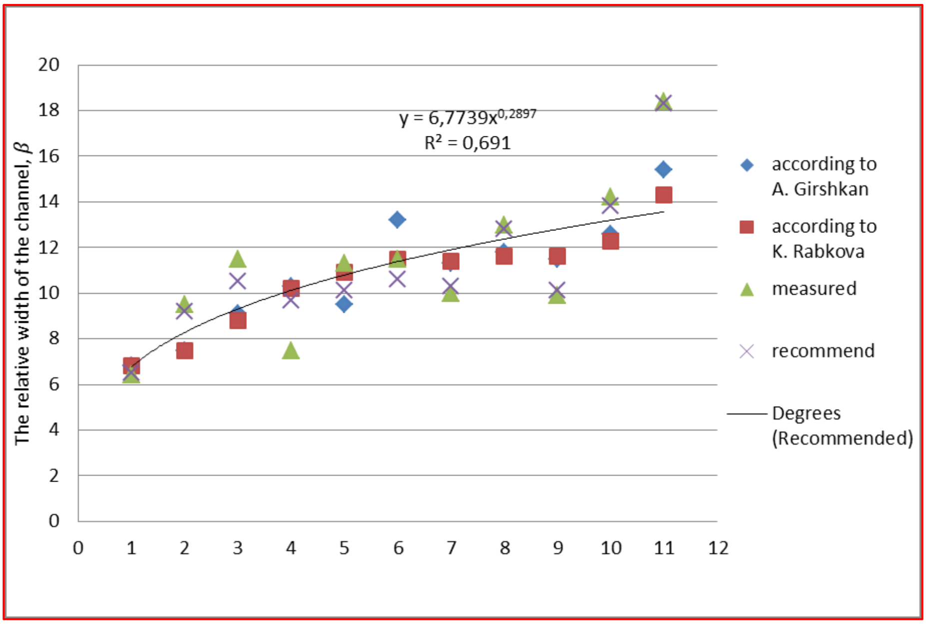

Fig. 1. Correlation index of the recommended method.

4 Conclusion

As can be seen from the comparison of the results of existing methods for the relative width of the flow in earthen channels, proposed by V.S. Altunin, S.A. Girshkan, and E.K. Rabkova, formulas give a large deviation from the natural parameters. The reason for this is the underestimation of many factors characterizing the course of formation of hydraulic parameters depending on the mode of movement and the interaction of the flow and the soil of the channel bed. As can be seen from table 1, under the same conditions, the relative channel width according to the existing methods has high deviations from the measured parameters in comparison with the proposed option. As the calculation results show, the proposed option's relative channel widths were close to the design data. Hence, it can be concluded that the proposed dependence for the relative flow width in the channels of the earthen channel, based on the theory of the turbulent movement of the flow, taking into account the interaction of the flow and the soil of the channel bed, is adequate in comparison with the known dependencies.

Thus, based on the analysis of the model of turbulent fluid motion, a mathematical model is proposed that describes the cross-sectional shape of statically and dynamically stable channels. The peculiarity of the method lies in the fact that here the hydraulic elements of the channel are determined directly from the model of the flow in the channel, taking into account the factors characterizing the elements of channel processes.

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