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Article

New Method For Hydraulic Calculation of High-Velocity Flows With Enhanced Roughness

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Abstract: This article presents a new method for hydraulic calculation of high-velocity flows in channels with enhanced roughness, primarily focused on flows with square cross-sectional obstacles. The effect of air entrainment in high-velocity flows is also considered, and examples of applying the method to design options aimed at achieving a specified depth or velocity are provided.

Keywords: Flow Velocity, Flow Depth, Relative Slope, Rotating Turbulent Waves, Uniform Flow

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1. Introduction

Existing methods for hydraulic calculation of high-velocity flows in channels with enhanced roughness are limited, particularly in terms of accuracy and applicability across a wide range of conditions. These methods often lack sufficient experimental validation and do not adequately account for factors such as air entrainment, and the complex flow characteristics in channels with varying roughness properties. Developing a more robust and accurate method is crucial for the efficient and safe design of hydraulic structures, including irrigation canals and other hydraulic projects' water-affected parts. The focus on enhanced roughness stems from its practical application in modifying flow regimes to achieve desired velocities and depths, and in mitigating problems such as turbulence and standing waves. The ability to accurately predict the effects of enhanced roughness is essential for optimizing the design and performance of such structures.

Enhanced roughness is used in high-velocity flows of water conduits, in irrigation canals, and in the water-affected parts of hydraulic structures to create desired flow regimes. [6]

The ultimate purpose of using enhanced roughness can vary - to reduce flow velocity, increase depth, eliminate circulating surge waves, redistribute flow in the cross-section (for example, to eliminate standing waves) - but, at the base of all these measures, enhanced roughness primarily creates additional resistance, leading to a decrease in kinetic energy [1]. Therefore, all known research and proposals for calculating enhanced roughness are primarily aimed at assessing its role as a resistance factor [2]. Thus, a rational methodology for calculating rapid flows with enhanced roughness, like the calculation methodologies for all other river flows, can only be built based on a preliminary study of resistance laws, taking into account all the specific characteristics of river flows with enhanced roughness, and all factors that can significantly influence the formation of resistance [4].

Currently, there are three known methods for hydraulic calculations of rapid flows /1-10, 13/: [3] The Zamarin-Pikalov method /1, 2/ sufficiently defines (excluding aeration) the factors influencing the resistance coefficient of rapid flows. However, let's examine the shortcomings of this method, specifically in the case of a cross-sectional bed roughness [2]. This method is based on experiments conducted within a limited range, with calculations performed for three slopes: i = 0.06; 0.10; 0.15. This provides discrete relationships for the resistance coefficient for each studied slope, rather than a general relationship applicable across a wider range, as follows: [4]

$$\lambda = 8g(k + m\beta - n\alpha)^2 \qquad (1)$$

Where k, m, n are positive experimental numbers,

- relative width (b/h),
- relative depth (l/d).

These relationships do not have a sufficiently justified structure and do not conform to boundary conditions [1]. This can be easily observed: if $b \to \infty$ (smooth flow), then $\lambda \to -\infty$, and if $\Delta \to 0$ (river flow with ordinary resistance), then $\lambda \to -\infty$. For slopes i = 0.06; i = 0.10, the relationships are obtained by multiplying the right-hand side of a relationship of type (1) by a certain general multiplier for the slope i = 0.15, this multiplier depends on the slope [2]. The method of determining this multiplier is not indicated, but such an operation may raise objections and, possibly, this is why the relationships for slopes i = 0.06 and i = 0.10 do not fit well with the authors' own experimental data. For example, the average deviations of the λ values calculated using the calculated relationships from the experimental values for slopes i = 0.15; 0.10; 0.06 are respectively: [4]

$\Delta\lambda$ %= 8,7; 31,4; 20,9. but they were obtained through extrapolation and have not been verified experimentally [1]. In the last two editions of the hydraulic manual edited by P.N. Kiselev /8, 9/, along with the Zamarin-Pikalov method, the P.I. Gordienko method is also presented without indicating its limits of application, although these two methods contradict each other [9]. It is important to emphasize that both methods are proposed for the same stable torrential flow, which occurs when the h/ value is higher than a certain minimum , and these values are determined by the location between (b/) and are determined experimentally (for example, when b/Δ = 8α_o, = 3.0, and when b/λ = 10, = 3.3) [2]. The P.I. Gordienko method /10/, in any case, including for rapid flows with enhanced roughness, λ claims that the resistance coefficient (or the Chezy coefficient) is always constant [4].

$$\lambda = \text{const} \qquad (2)$$

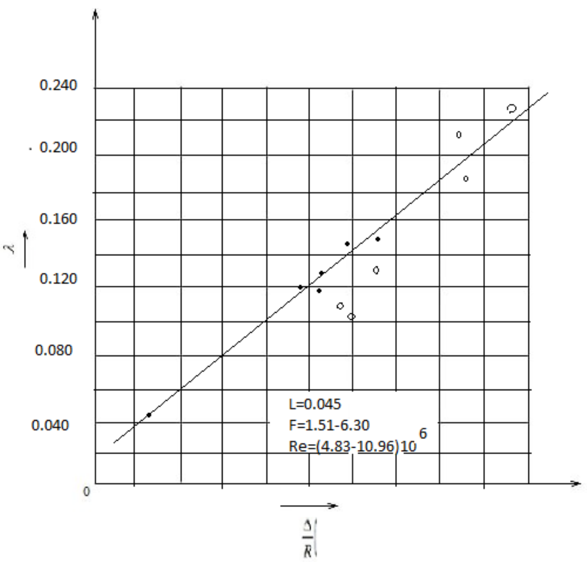
and depends only on the type of roughness and is independent of the relative roughness and hydraulic radius. As a result of using this method, it is impossible to calculate the height of the ribs, "Δ", which is the main parameter of enhanced roughness. [3] At the same time, it is indicated in this method that the height of the ribs must satisfy the following condition: $\Delta \le h/\alpha_o$ (condition for stable flow). However, it is unknown what the height of the ribs should be within the $\Delta = 0 \div h/\alpha_0$ range, which makes the method unacceptable for engineering calculations. [8]

It should be noted that the conclusions underlying the considered method do not have a solid experimental basis. The author's own experiments (i = 0.02 to 0.128) were conducted in a limited range. References to experiments by Straub and Anderson and 6 experimental points by E. Marki regarding smooth channels are clearly insufficient, as all other known experimental materials refute these conclusions. [4] For example, it is sufficient to refer to previous works by researchers such as Bazin, Deynile, Gerke, Kaplinsky, Latyshenko, Zamarin, Pikalov, Egorov, Falkovich, Vyazgo, Powell (as well as later laboratory and field research by Powell, Posey, Raspopin, [2] Ayvazyan), who reject the concept of enhanced (regular) roughness. From a large amount of practical data confirming that turbulent flows are not independent of relative roughness, we provide the following striking examples (Figures 1 and 2): natural data on rapid flow in the Yangi-Dargom canal [11], as well as [6] Bazin's experimental results from series 13 and 14 /12/, where diagrams showing the dependence of the resistance coefficient on relative roughness were developed by us. [4] The author of this article previously proposed /13/ a method for the hydraulic calculation of rapid flows with enhanced roughness in uniform flow, based on systematic experiments conducted within a range of slopes i = 0.05 to 0.57, which is four times wider than the range within which the researcher's previous experiments were conducted. Within this range, studies were carried out with the following slopes: [9]

i = 0.0512; 0.10; 0.17; 0.30; 0.57. Subsequently, the experimental data on the hydraulic resistance coefficient were generalized and presented as a single relationship for the entire interval i = 0.05 - 0.57:

$$\lambda = M + 2i^2 - N \cdot i \cdot \ell gi(\frac{\Delta}{\hbar} \cdot \frac{\beta}{\pi} \cdot \frac{4}{\sqrt{F}}) \quad (3)$$

Where M and -N are experimental numbers that depend on the type of enhanced roughness. [4]



Relationship graph for the rapid flow in the Yangi-Dargom canal h+k (Q=0.10 65.1 /s; experiment 11) [5]

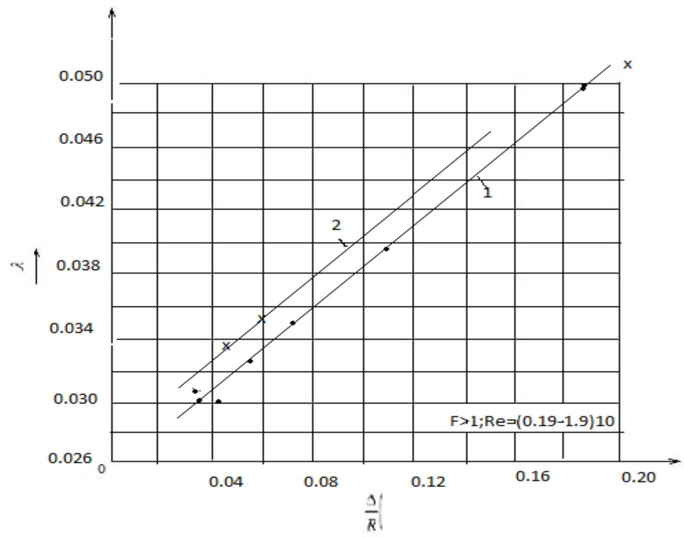


Figure 2. Bazin's experiments. Graphs of the relationship of $\lambda = f(\frac{\Delta}{h})$ for series 13 and 14 (Q= $0.10 \div 1.236 m^3 / c$ m; 13 experiments); 2 - corresponds to i=0.0053: 0.00886.

Relationship (3) and the calculation method based on it form the basis.

In formula (3), the values of h, X (wetted perimeter), and F (Froude number) apply to a flow that is saturated with air to one degree or another. [2] To account for this situation, when assessing the actual flow velocity, along with formula (3), an experimental table is proposed for the ratio of the velocity determined by the live surface saturated with air to the velocity of the actual liquid phase. [3]

The relationships in formula (3), which forms the basis of the method, are strengthened by extensive experimental studies, the results of which correspond to the main mass common with previous studies. This is well illustrated by the composition of the arguments on the right-hand side of formula (3) and the data presented in Figures 1 and 2.

Formula (3) satisfies the boundary conditions and matches the experimental data with an average quadratic deviation of $\Delta\lambda = \pm 9\%$. [9]

2. Materials and Methods

The results presented in the work allow for the creation of an effective method for hydraulic calculation of rapid flows, which is considered as a case of calculating open channels. In particular, based on the new general formula: [8]

$$\lambda = f(y, \frac{\Delta}{R})$$

While preserving all the advantages mentioned above, this method can be significantly simplified. Since the rapid flows under consideration are only covered with enhanced roughness at the bottom, the right side of formula (4) should be supplemented with the ratio of the bottom width to the wetted perimeter (b/x). [4] This ratio determines the share of the wetted perimeter covered by enhanced roughness [2].

Note:

1. O.M. Ayvazyan, "Calculation of the Darcy Coefficient for Open Flows," in this collection, page 114.

$$\lambda = f(y, \frac{\Delta}{R}, \frac{B}{x})$$

Based on relationship (5), the reprocessing of experimental data on regular roughness (transverse bottom ribs with a square cross-section b= 8Δ; = 0.05; 0.10; 0.17; 0.30; 0.57; Δ = 0.4; 0.5; 0.7; 0.8; 1.0 cm) gives the following formula for the Darcy coefficient for rapid flows with enhanced bottom roughness in the form of transverse ribs with a square cross-section placed at distances between the axes of b= 8Δ; [10]

$$\lambda = 0.035 + 1.68i^2 + (0.6 + 1.75i)\frac{\Delta}{R}(\frac{b}{x})^2$$

For rapid flows with rectangular cross-sections:

$$\frac{\Delta}{R}(\frac{b}{x})^2 = \frac{\Delta}{h}(\frac{b}{x})$$

and formula (6) is slightly simplified

$$\lambda = 0.035 + 1.68i^2 + (0.6 + 1.75i)\frac{\Delta}{h}(\frac{b}{x})$$

Formula (6) generalizes all experimental data very well (145 experiments, in the range from L = 0.05 to 0.57) [2], both in terms of average and mean squared errors, and in terms of the characteristics of the distribution of these errors.

The values of the average and mean squared errors, calculated on the basis of formula (6), for the Darcy and Chezy coefficients, as well as for the depths, and their deviations from the experimental values are given in the table. Figure 3 shows the areas of experimental points corresponding to different angles, along with the curves of formula (6) corresponding to those angles. :[3]

The table contains data on the absolute values of the errors, as well as the ratios between the average and mean squared errors.

1. See O.M. Ayvazyan, "Calculation of the Darcy Coefficient for Open Flows," in this collection, page 114.

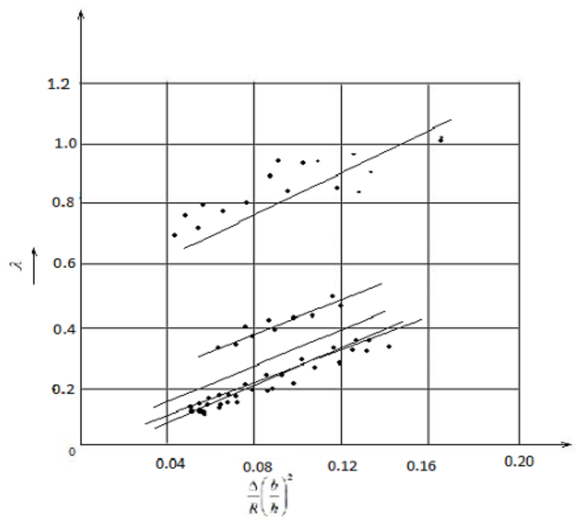


Figure 3. Author's experiments. Transverse bottom ribs with *б*=8 Δ ; 1,2,3,4,5 - the curves of the calculation formula (6) at slopes *i*=0.0512; 0.10;0.17;0.30;0.57.

Table of Deviations

i	Number of Experiments	$(\Delta\lambda)cp$ %	$(\Delta\lambda)c.kb$ %	$(\Delta c)cp$ %	$(\Delta c)c.kb$ %	$(\Delta h)cp$ %	$(\Delta h)c.kb$ %
0.0512	34	± 9.1	± 11.2	± 4.2	± 5.5	± 2.8	± 3.4
0.10	32	± 11.0	± 13.7	± 5.0	± 6.3	± 3.3	± 4.0
0.17	42	± 9.6	± 11.3	± 4.5	± 5.5	± 3.0	± 3.4
0.30	13	± 6.9	± 9.23	± 3.3	± 4.3	± 2.3	± 2.9
0.57	24	± 8.9	± 9.75	± 4.1	± 4.5	± 2.7	± 3.0

The mutual location of the experimental points and the calculated curves (see Figure 3) indicates that the accuracy of formula (6) is sufficient. [10]

However, considering the difficulties that arise in determining the location of the turbulent and pulsating free surface, especially for aerated rapid flows in a channel with a ribbed rough surface, and considering the double averaging associated with averaging over time and cross-section, it is not difficult to show that based on the error values for the depths given in the table, the correspondence of formula (6) to experiments is within the boundary zone. [3] Formula (6) has an experimental basis in the ranges of the main dimensionless characteristics and is practically as wide as in engineering practice: [1]

$$F > 0; i = 0.05 \div 0.57; h / \Delta = 3 \div 20; b / h = 3.5 \div 23.0;$$

Thus, the first and main condition necessary to create an effective method for hydraulic calculation - the availability of a reliable relationship for the hydraulic resistance coefficient - is satisfactorily met in the form of formula (6). [2] The following steps involve only applying this basic formula and involving other necessary relationships.

Based on formula (6), solving for determining the height of the roughness with constant ribs can be expressed as follows:.[4]

$$\Delta = R\left(\frac{x}{b}\right)^2 \frac{[\lambda] - 0.035 - 1.68i^2}{0.6 + 1.75i}$$

Where:

[λ] - the resistance coefficient corresponding to the hydraulic regime;

Δ -the height of the ribbed roughness that ensures this regime.

According to the Darcy-Weisbach (or Chezy) formula: [10]

$$[\lambda] = \frac{8gRi\omega^2}{Q^2}$$

In formulas (8) and (9), all parameters represent the characteristics of the live section (ω , x, R) that correspond to the hydraulic regime. [2] Formulas (6), (8), and (9) emphasize that all their geometric characteristics of the live section relate to the water-air mixture, where Q is the flow rate being passed. Rapid flows with enhanced roughness are often aerated to one degree or another: [3]

Only the liquid phase. Due to the indicated feature, there can be two different cases of using formula (8). The first case occurs when a ribbed surface is used to create a certain depth in a rapid flow, i.e., this depth is greater than the depth that existed without using enhanced roughness. [8] The designer knows that with an increase in the depth at the water barrier, the velocity also decreases. [4] However, he is interested in the depth, not the new velocity value [12]. In this case, the value of the required depth [h] is used in calculating

the live section characteristics (ω, x, R) given in formulas (9) and (8), and as a result, the required rib height is determined. [6] The second, more complex calculation case occurs when covered gravel surfaces are used in a rapid flow to create a certain liquid phase velocity [V], i.e., this velocity is lower than the velocity that existed without using enhanced roughness, and is based on the given parameters *Q, i, b* and m [13].
In this case, first, the required live cross-section area of the water-air mixture is determined based on the following formula: [1]

$$\omega = \frac{Q}{[V](1-a)}$$

Where a is the aeration coefficient. Based on this area value, ω, other characteristics of the live section (X, R) are determined, and then the required height of the ribs (Δ) is determined [14].

As we can see, the necessary condition for performing these calculations is that the aeration coefficient is known. We conducted the study of this coefficient using experimental values. :[3]

The aeration coefficient is the ratio of the air-filled part of the live cross-section to the full live cross-sectional area. [2]

Average velocities V were determined based on local velocity point measurements and velocities measured using sinking floats, and V_ω velocities were calculated as the flow of the liquid phase divided by the live cross-section area. [10]
Aeration coefficients were determined using the following expression:

$$a = 1 - \frac{V_\omega}{V}$$

The results obtained in this way, /14/, suggest the following relationship, i.e., for determining the aeration coefficient for enhanced roughness in rapid flows:

$$a \approx i$$

According to the relationship (12), the aeration coefficient in rapid flows with enhanced roughness can be approximately equal to the degree of the bottom slope of the rapid flow. Thus, the proposed new calculation method is based on the relationships (6), (8), (9), (10), and (12) in the calculation of rapid flows with enhanced roughness: [7]

3. Result and Discussion

Example of Calculation Using the New Method

A concrete rectangular rapid flow has the following characteristics: [5]
b = 2,0 м; *i* = 0,151; n = 0,017; Q = 6,7 м³/с.

As a result of the calculation, it is determined that if the motion is uniform, the depth in the rapid flow will be h_0 = 0.35 m and the velocity will be V_0 = 9.5 m/s. [3] It is required to calculate the enhanced roughness in order to reduce the liquid phase velocity to [V] = 6.5 m/s [15].

According to the relationship (10), we calculate the required water-air mixture area, taking the aeration coefficient equal to the degree of the bottom slope, in accordance with the relationship (12). [2]

$$\omega = \frac{Q}{[V](1-a)} = \frac{6.7}{6.0(1-0.151)} = 1.31m^2$$

We determine the other characteristics of the live section:

$$h = \frac{\omega}{B} = \frac{1.31}{2} = 0.655M$$

$$x = B + 2h = 2 + 1.31 = 3.31M,$$

$$R = \frac{\omega}{\lambda} = \frac{1.31}{3.31} = 0.396M$$

Using the formula, determine the required value of the resistance coefficient:

$$[\lambda] = \frac{8gRi\omega^2}{Q^2} = \frac{8 \cdot 9,8t \cdot 0,396 \cdot 0,151 \cdot 1,31^2}{6,7^2 \cdot} = 0.180.$$

Based on the formula, we determine the required rib height. [5]

$$\Delta = R(\frac{x}{6})^2 \frac{[\lambda] - 0,035 - 1,08i^2}{0.6 + 1,75i} =$$

$$= 0.396(\frac{3.31}{2})^2 \frac{0.180 - 0.035 - 1.68 \cdot 0.151^2}{0.6 + 1.15 \cdot 0.151} = 0.134m.$$

The result is realistic because

$$\frac{h}{\Delta} = \frac{0,655}{0,134} = 4,9 > 3$$

We set the rib height to Δ = 0.13 m. The distance between the axes of the ribs is b = 8Δ = 1.10 m.

4. Conclusion

The above-presented method for calculating rapid flows is based on relationships obtained based on regular roughness, i.e., transverse ribs with a square cross-section installed on the bottom [16], and the distance between them is equal to eight times their height between the axes:

b = 8 Δ

The proposed calculation method is considered correct if the ratio between the water flow depth (measured from above the rib height) and the rib height is as follows: .[4]

$h/\Delta > 3$,

This ensures uniform movement and prevents turbulence [17]. If the rib height obtained by calculation violates this condition (i.e., h/Δ > 3), the calculation results are considered incorrect. [5] This means that the required regime cannot be achieved by design - the resistance created by the ribs will be less than the required resistance in the case of uniform motion. [3] Conversely, a negative value of the rib height indicates that the resistance created in this regime is more than required. [6]

The relationships (6), (8), and (12) form the basis of the proposed calculation method and have been experimentally verified within the following ranges of the main dimensionless characteristics: [5]

$$F > 0; i = 0.05 \div 0.57; h / \Delta = 3 \div 20; b / h = 3.5 \div 23.0;$$

These ranges almost coincide with the ranges encountered in engineering practice [18]. Since the relationships (6), (8), and (12) have proven themselves over very wide ranges, they can be extrapolated beyond the boundaries indicated above, if necessary, if F > 1. [5]

When determining the enhanced roughness in rapid flows, it is also necessary to indicate the length of the section of the water flow that needs to be provided with ribs [19]. If the ribs are used to create a specific depth (or velocity), they should be installed at a point where the flow depth or velocity is less than required [7,11].

If enhanced roughness is used only at the exit of the rapid flow (a regime designed to facilitate the impact of water), in order to create a specific regime, in this case, the ribs are installed only in the final section of the flow, and the length of this section should be such that it is sufficient to ensure uniform movement at its end. According to our research /15/, to determine this length, the following relationship can be recommended:

$$l_{\Delta} \approx 20h, \tag{13}$$

where h is the depth taken as the basis for calculating the rib height [20].

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