ISSN: 2350-0328
International Journal of AdvancedResearch in Science, Engineering and Technology
Vol. 12, Issue 2, February 2025

Investigation of hydraulic resistance of turbulent non-aerated flows in concrete channels

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ABSTRACT: This paper presents the results of a study on the hydraulic resistance of turbulent, non-aerated flows in concrete channels, conducted based on laboratory and field experiments. It was established that the patterns of hydraulic resistance of turbulent flows differ significantly from those of tranquil flows. For describing the hydraulic resistance of turbulent flows in smooth-walled and reinforced concrete flumes and channels, the O.M. Ayvazyan formula was successfully applied. During laboratory studies on a specially designed setup, the parameters of this formula for concrete flumes were determined. Field studies conducted on various canals in the Kashkadarya region of Uzbekistan confirmed the applicability of the obtained formula and the established parameters for calculating the hydraulic resistance of turbulent flows in concrete channels. The results obtained allow for more accurate calculation of the hydraulic resistance of turbulent flows in concrete channels, which is of great importance for the design and operation of hydraulic structures.

KEYWORDS: Hydraulic resistance, turbulent flows, non-aerated flows, concrete channels, O.M. Ayvazyan formula, laboratory studies, field experiments, hydraulic calculation, hydraulic structures.

I.INTRODUCTION

The relevance of the topic is driven by the need to improve the accuracy of calculating the hydraulic resistance of turbulent, non-aerated flows in concrete channels. Existing calculation methods are often inadequate for such flows, leading to errors in the design and operation of hydraulic structures. Developing more accurate calculation methods based on experimental data is an important task for ensuring the safety and efficiency of hydraulic facilities. The research presented in this paper aims to address this pressing issue. Accurate determination of hydraulic resistance in open channel flows is paramount for the reliable design and efficient operation of hydraulic structures, particularly in irrigation and water conveyance systems.

While significant progress has been made in understanding flow behavior in various channel types, the specific characteristics of turbulent, non-aerated flows in concrete channels require further investigation. Existing calculation methods often fall short in accurately predicting hydraulic resistance under these conditions, potentially leading to design inefficiencies and compromised operational safety.

This research addresses this critical need by presenting a comprehensive study of hydraulic resistance in turbulent, non-aerated flows within concrete channels. Building upon the foundational work of O.M. Ayvazyan and previous investigations into smooth-walled and reinforced concrete flumes [1], this paper aims to:

1. Characterize the unique hydraulic resistance patterns of turbulent flows in concrete channels, contrasting them with tranquil flow regimes.

2. Validate the applicability of the O.M. Ayvazyan formula for describing hydraulic resistance in turbulent flows within concrete channels.

ISSN: 2350-0328
International Journal of AdvancedResearch in Science, Engineering and Technology
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3. Determine specific parameter values for the O.M. Ayvazyan formula that accurately represent the observed hydraulic behavior in concrete channels, through a combination of laboratory and field experiments.

4. Evaluate the accuracy and reliability of the proposed methodology for hydraulic calculations in practical engineering applications.

II. MATERIALS AND METHODS

Construction and utilization of a large-scale (50.8 m long) rectangular concrete flume with controlled slope, enabling manipulation of flow conditions and Field Experiments, conducting measurements in existing, operational concrete-lined canals (Mumminabad, Chorchanba, Left Bank Tanhos, Right Bank Tanhos) within the Kashkadarya region of Uzbekistan. For measurements in the installation, a precision level, point gauges, a tape measure with 1 mm graduations, a mercury thermometer, a triangular measuring weir, and a Pitot-Rehbock tube are used.Specifically, turbulent flows are characterized by a unique type of mixed resistance, which, under conditions of A=const.; v=const., is analytically described by the O.M. Ayvazyan formula.

$$\lambda = a + KI^{x}R^{z}$$

With $K < 0; x < 0; z < 0.$

When represented in traditional Nikuradze coordinate graphs, the unknown characteristic of the hydraulic resistance of turbulent flows [1] manifests as an increase in the coefficient with increasing R under conditions of $\mathrm{Re} = const;$ $\Delta = const;$

In [1], the inability to accurately calculate the coefficient of 1 and Chezy (C = 8g/A) for turbulent flows in smooth or reinforced concrete channels and flume using existing traditional and non-traditional formulas was demonstrated, as was the impossibility of generalizing laboratory and field experimental data based on them. To address this, formula (1), a specific form of the general formula [1] (when D=const.; y=const.), was successfully employed.
The following values for the constants in formula (1) were established for non-aerated, uniform, turbulent flows:

III. RESULTS AND DISCUSSIONS.

Smooth-walled flumes:

a=0,022; $K+ = -0.0001$ M^{-z}; x=-0,2; z=-1;
precast reinforced concrete (with joint misalignments within 30 mm) flume channels;
a=0,028; K*=-0,003 M^{-z}; x=-0,2; z=-1.
It should be noted that in hydraulic engineering practice, turbulent flow mainly occurs in concrete chutes of various purposes. Therefore, it is important to continue the investigation of the issues raised in [1], focusing on turbulent flows in concrete channels.

These K values correspond to the average value $v = 10^{-6} m^{2} / c$ for smooth-walled flumes: $v = 1.05 \cdot 10^{-6} m^{2} / c$ for precast reinforced concrete flumes, and $v = 1.087 \cdot 10^{-6} m^{2} / c$ for concrete flumes.

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International Journal of AdvancedResearch in Science, Engineering and Technology
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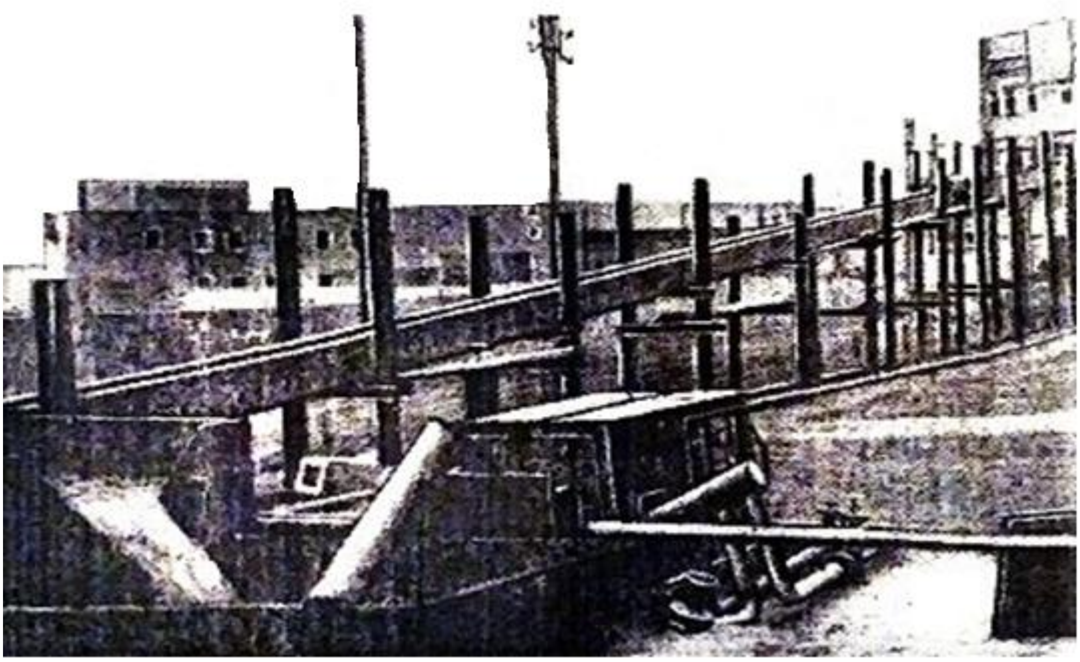

Let us present the results of such a study under laboratory and field-production conditions.

To conduct the laboratory study, a large-scale installation (Fig. 1) was designed and built on the open grounds of the Kashin branch of TIIIMSX.

. The setup allows for investigations at varying slopes, which are achieved by dismantling and reassembling sections and transverse supporting channels using a crane, enabling slopes of $0 \le i \le 0.1$ The establishment of the flume at a given slope is done by reassembling the constituent sections and transverse supporting channels with the aid of a crane. The experimental flume is equipped with upstream and downstream gates. The setup is supplied via a circulation system by a centrifugal pump ($Q_{МАКС}$ =120 л/с; $H_{МАКС}$ =20 м), which delivers water into the head settling tank of the flume.

Uniform turbulent flow at low discharges was established naturally due to the length of the flume. At higher discharges, uniform flow was achieved by vertically constricting the flow with the upstream gate. The presence of uniform flow (h = constant = h_0) was confirmed by measuring the depth (averaged over three verticals) at two control sections located at distances of 27.7 and 42.7 m from the flume's inlet section. Turbulent, uniform, non-aerated flows were investigated in four series at flume slopes of i = 0.0102, 0.0392, 0.0596, and 0.081, with the following intervals of changes in the main hydraulic characteristics of the flows:

$$Q = 6{,}15 - 100\ l/c;\ I = 0{,}0102 - 0{,}081;\ ho = 0{,}014 - 0{,}161 м;\ Re\ \left(0{,}0703 - 0{,}732\right)\ - 10^5;$$

$$Fr = 1{,}56 - 43,\ 59;\ N = 27.$$

A series of experiments with tranquil flows was also conducted at a flume slope of $i = 0.00101$, within the following ranges of flow characteristics: $Q = 1.21 - 38.86\ l/s;\ I = 0.00101;\ h_0 = 0.0219 - 0.234 M;$

$$Re = \left(0{,}133 - 2{,}056\right)\ - 105;\ Fr = 0{,}129 - 0{,}153;\ N = 9.$$

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The depth of uniform flow for tranquil flows was determined using the well-known indirect method of A. P. Zagodya [2]. The measurement data obtained in the laboratory experiments are presented in Table 1. Based on these data, derived quantities were calculated, some of which are also presented there. The experimental values for the resistance coefficient, Reynolds number Re, Froude number Fr, and Manning's roughness coefficient were determined using the following expressions:

$$\lambda = 8gRI / v^2; \ \mathrm{Re} = 4vR / \nu$$

$$Fr = av^2 / gh; \ n = R^{2/3} I^{1/2} / v.$$

When calculating the Froude numbers Fr, the values of the Coriolis coefficient (α) were used, established based on the velocity field measured in each specific case.

Table 1

Experimental data for uniform non-aerated flows in laboratory concrete flumes.

b=0,32 м; m=0; t=50 м

Experiment	I	Q, l/c	h_0, c	t^o, см	R, см	λ	$\mathrm{Re}\cdot 10^{-5}$	Fr	n
1	0.0102	6.15	1.96	23.0	1.75	0.0151	0.703	5.32	0.0071
2	0.0102	15.70	4.06	20.0	3.24	0.0177	1.567	4.03	0.0085
3	0.0102	24.29	6.12	22.9	4.43	0.0231	2.289	2.82	0.0102
4	0.0102	31.13	7.54	23.1	5.12	0.0246	2.781	2.48	0.0108
5	0.0102	43.56	9.93	20.0	6.13	0.0261	3.328	2.12	0.0115
6	0.0102	59.80	12.96	20.0	7.16	0.0277	4.079	1.79	0.0121
7	0.0102	77.28	16.11	19.2	8.03	0.0286	4.675	1.56	0.0125
8	0.0392	11.32	2.01	12.9	1.77	0.0178	1.041	17.28	0.0077
9	0.0392	27.75	4.03	12.0	3.22	0.0214	2.235	12.28	0.0093
10	0.0392	35.59	4.07	12.9	3.79	0.0233	2.804	11.30	0.0100
11	0.0392	44.20	5.98	12.7	4.35	0.0251	3.308	10.08	0.0106
12	0.0392	53.16	6.93	12.9	4.84	0.0259	3.836	9.30	0.0110
13	0.0392	73.58	9.03	12.7	5.79	0.0276	4.837	8.00	0.0117
14	0.0392	100.35	11.75	13.0	6.77	0.0292	5.989	6.80	0.0123
15	0.0596	10.36	1.59	20.0	1.47	0.0163	1.186	29.27	0.0078
16	0.0596	22.45	2.87	16.1	2.43	0.0190	2.141	23.40	0.0080
17	0.0596	30.79	3.74	16.1	3.03	0.0214	2.803	19.85	0.0090
18	0.0596	44.48	5.12	17.0	3.88	0.0246	3.870	16.14	0.0103
19	0.0596	54.87	6.09	17.0	4.39	0.0259	4.541	14.65	0.0108
20	0.0596	75.08	78.86	16.1	5.27	0.0277	5.669	12.71	0.0115
21	0.0596	100.13	9.93	16.1	6.15	0.0293	6.948	11.04	0.0121
22	0.0810	10.45	1.40	17.0	1.29	0.0151	1.104	43.59	0.0067
23	0.0810	38.00	3.98	16.9	3.19	0.0228	3.493	25.08	0.0096
24	0.0810	52.20	5.18	16.9	3.91	0.0231	4.518	21.46	0.0104
25	0.0810	58.16	5.68	18.6	4.19	0.0260	5.107	20.21	0.0107
26	0.0810	74.69	6.95	17.0	4.85	0.0274	5.973	18.17	0.0113
27	0.0810	98.80	8.76	17.0	5.66	0.0290	7.321	15.90	0.0119
28	0.00101	2.79	3.96	20.0	3.181	0.0520	0.280	0.137	0.0145
29	0.00101	5.22	5.94	21.8	4.33	0.0955	0.480	0.142	0.0143

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International Journal of AdvancedResearch in Science, Engineering and Technology
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30	0.00101	6.76	7.03	20.0	4.90	0.0431	0.589	0.144	0.0142
31	0.00101	8.36	8.08	21.8	5.37	0.0407	0.702	0.143	0.0140
32	0.00101	10.06	9.14	21.0	5.82	0.0390	0.806	0.145	0.0139
33	0.00101	13.15	10.78	22.9	6.44	0.0351	1.023	0.151	0.0134
34	0.00101	19.78	17.34	22.9	7.56	0.0324	1.357	0.195	0.0132
35	0.00101	24.76	16.64	21.8	8.16	0.0299	1.537	0.146	0.0129
36	0.00101	38.86	23.40	22.9	9.50	0.0279	2.056	0.128	0.0129

Coordinates of experimental resistance curves (uniform turbulent non-aerated flows in concrete laboratory flumes and field canals)

Figure 2 (curves 1, 2, 3) shows graphical interpretations of the experimental data from Table 1 for turbulent flows, plotted in the coordinates $\lambda = \lambda\ (\mathrm{Re})$ with Δ/R = const, which are commonly used in fluid mechanics and hydraulics. Given that all series of experiments were conducted with constant roughness of the concrete flumes, i.e., with Δ = const

Table 2

Laboratory

R, M	I	Lg (100λ)	Lg Re
0.02	0.0102	0.228	4.994
	0.0392	0.246	5.05
	0.0596	0.258	5.111
	0.0810	0.267	5.233
0.04	0.0102	0.350	5.294
	0.0392	0.378	5.502
	0.0596	0.398	5.626
	0.0810	0.407	5.679
0.06	0.0102	0.420	5.558
	0.0392	0.446	5.712
	0.0596	0.459	5.800
	0.0810	0.468	5.873

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Field

0.30	0.01173 0.01538 0.0203 0.02563 0.02917	0.513 0.516 0.517 0.518 0.519	6.508 6.632 6.651 6.709 6.816
0.50	0.01173 0.01538 0.0203 0.02563 0.02917	0.523 0.525 0.526 0.526 0.526	6.787 6.84 6.85 6.88 7.03

Subsequently, this data was generalized into a formula

$$a = 1,05 \ + \ 0,195 / \beta$$

where β is the relative width of the flume $\beta = b / h$

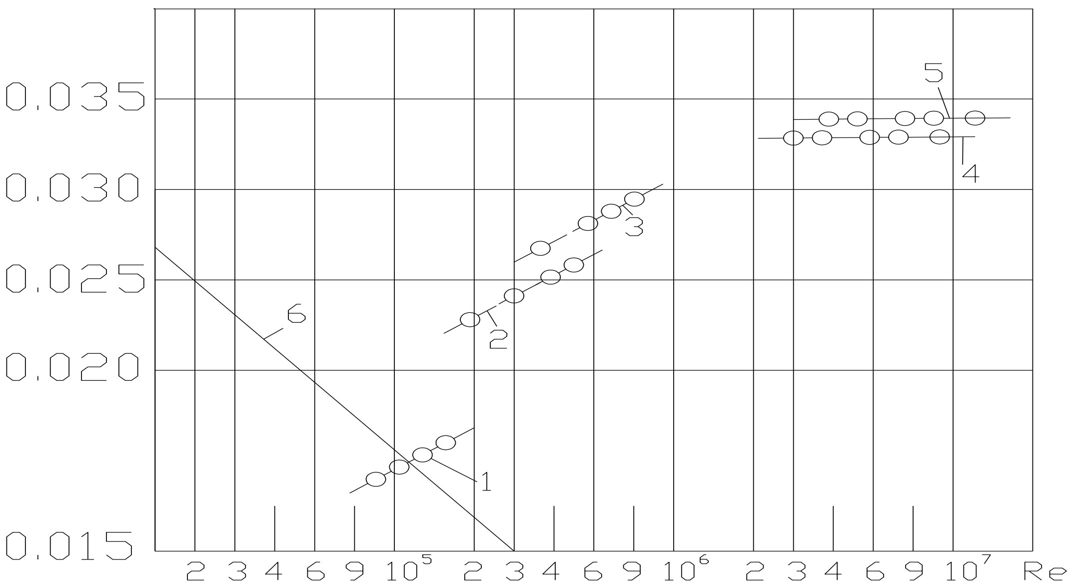

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Fig. 2. Experimental resistance curves for turbulent uniform non-aerated flows in concrete channels: 1, 2, 3 – laboratory flumes (R=0.02; 0.04; 0.06 m, respectively); 4, 5 – field canals (R=0.3; 0.5 m, respectively); 6 – Prandtl-Karman formula curve $(1/\sqrt{\lambda} = 2\lg \mathrm{Re}\sqrt{\lambda} - 0.8)$ for smooth pipes.

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Table 3

Experiment	Q, M ^{3}/c	h_0, M	R, см	v, m/c	λ	t^o, c	$Re \cdot 10^{-5}$	Fr	n
Mubinbad Canal *i*=0.01173; b=1.60 M; b=1.60 M; m=1.54									
1	5.955	0.66	0.428	3.448	0.03322	18.0	5.57292	2.802	0.0179
2	5.675	0.64	0.419	3.429	0.03250	20.0	5.59010	2.844	0.0175
3	4.476	0.56	0.377	3.246	0.03294	22.4	5.098925	2.844	0.0174
4	4.313	0.55	0.372	3.204	0.03336	23.0	5.12640	2.814	0.0184
5	3.311	0.47	0.328	3.032	0.03285	18.0	3.74681	2.885	0.0170
6	2.438	0.39	0.283	2.841	0.03228	18.0	3.02912	2.953	0.0165
7	2.222	0.36	0.266	2.863	0.03178	18.0	2.86820	3.210	0.0064
8	1.162	0.31	0.235	2.581	0.03247	19.0	2.34183	2.957	0.0160
9	1.558	0.29	0.223	2.623	0.02984	19.0	2.25841	3.234	0.0158
10	1.204	0.24	0.191	2.545	0.02715	19.0	1.87681	3.589	0.0141
Chorshanba Canal (ПК 105-108) *i*=0.01538; b=1.80; m=1.45.									
11	7.421	0.67	0.446	3.998	0.03368	23.0	7.66928	3.600	0.0181
12	6.397	0.61	0.413	3.932	0.03224	18.9	6.24583	3.857	0.0178
13	5.388	0.54	0.377	3.862	0.03051	23.0	6.26225	4.077	0.0168
14	5.004	0.53	0.369	3.704	0.03246	18.0	5.15278	3.803	0.0174
15	4.392	0.49	0.347	3.600	0.03232	23.0	4.80462	3.871	0.0172
16	3.716	0.44	0.320	3.463	0.03221	18.0	4.22160	3.885	0.0170
17	3.224	0.38	0.285	3.610	0.02635	23.0	4.42516	3.746	0.0149
Chorshanba Canal (сбросной) *i* =0.01946; b=1.40; m=1.52.									
18	4.829	0.54	0.355	4.042	0.03319	20.0	5.68281	4.649	0.0172
19	4.247	0.50	0.335	3.932	0.03309	18.2	5.01738	4.688	0.0171
20	3.743	0.46	0.316	3.843	0.02368	19.1	4.71607	4.761	0.0170
21	2.904	0.40	0.281	3.616	0.03282	19.1	3.94600	4.767	0.0165
22	2.573	0.37	0.263	2.579	0.03134	23.0	4.050766	5.043	0.0160
23	2.122	0.33	0.243	3.379	0.03250	18.0	3.09556	5.097	0.0160
Left Bank Tankhoz Canal (ПК 26.10-29.0) *i*=0.02107; b=1.24; m=1.23.									
24	4.596	0.56	0.358	4.256	0.03268	22.4	6.28308	4.908	0.0174
25	3.631	0.49	0.323	4.021	0.03303	19.1	5.04382	4.859	0.0170
26	3.118	0.45	0.301	3.898	0.03276	20.0	4.64673	4.940	0.0167
27	2.402	0.38	0.267	3.662	0.03292	20.0	3.87229	4.996	0.0164
28	1.799	0.32	0.232	3.440	0.03242	18.3	3.04030	5.150	0.0159

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Left Bank Tankhoz Canal (ПК46-49+70) *i*=0.02563; b=1.10; m=1.32.									
29	5.384	0.60	0.368	3.697	0.03355	20.1	6.84553	6.002	0.0173
30	3.740	0.49	0.314	4.369	0.03309	19.2	5.32764	6.001	0.0169
31	2.995	0.43	0.284	4.176	0.03276	19.3	4.60676	6.136	0.0167
32	2.425	0.38	0.258	3.982	0.03273	18.1	3.91174	6.131	0.0163
33	1.641	0.30	0.215	3.665	0.03237	19.4	3.05475	6.338	0.0157
Right Bank Tankhoz Canal *i* =0.02917; b=0.97; m=1.37.									
34	2.589	0.40	0.261	4.265	0.03275	22.9	4.68701	6.957	0.0163
35	2.473	0.39	0.256	4.213	0.03302	20.1	4.27140	6.917	0.0161
36	1.961	0.34	0.230	4.018	0.02261	21.2	3.73390	7.038	0.0160
37	1.325	0.27	0.192	3.688	0.03232	19.0	2.74789	7.204	0.0154
38	1.021	0.23	0.169	3.449	0.03252	21.1	2.42867	7.190	0.0151
39	1.041	0.22	0.163	3.718	0.02699	18.0	2.30270	8.674	0.0137

The condition Δ /R = const is equivalent to the condition R = constant, which was used in constructing curves 1, 2, and 3. The coordinates of these curves, presented in Table 2, were derived from the auxiliary families of curves $\lambda = \lambda(\mathrm{Re})$ at I = constant and $\lambda = \lambda$ (R) at I = constant, which were constructed directly from the data in Table 1 (experiments 1-27). Figure 2 does not include data from the study of tranquil flows (experiments 28-36); these were conducted at a constant slope, and the data set does not allow for the construction of curves $\lambda = \lambda(\mathrm{Re})$ at R = const. The positions of curves 1, 2, and 3 in Figure 2 show that the zone of mixed resistance for turbulent flows in the concrete channels they represent differs from descriptions in hydraulics and fluid mechanics textbooks, but is identical to the resistance zone for turbulent uniform flows in smooth and precast/reinforced concrete channels [1].

Traditional or other formulas used for calculating the resistance coefficient (1) or the Chezy coefficient (C) for uniform flows cannot be used either for the mathematical generalization of the experimental data in Table 1 for turbulent flows in concrete flumes, or for their hydraulic calculation. Based on the above and experience [1], the mathematical generalization of the data in Table 1 for turbulent flows was carried out using formula (1), and the following values of its parameters were established for non-aerated turbulent flows in concrete flumes:

$$a=0{,}035;\ K^*=-0{,}000225\ \text{м}^{-z};\ x=-0{,}2;\ z=-1. \qquad (3)$$

It should be noted that formula (1) with the parameter values (3) is valid if the following condition is met:

$$R_{(M)} \geq (0.011/I^{0.2}) \qquad (4)$$

It should be noted that formula (1) with the parameter values (3) is valid if the following condition is met:

$$R_{(M)} \geq (0.011/I^{0.2}) \qquad (4)$$

which is very close to the analogous condition for smooth-walled flumes [1]. In the opposite ratio, there is a tendency for the resistance coefficient to remain constant, which, at high-velocity slopes, occurs at small values of the hydraulic radius, which are not of practical interest. For example, out of the rows in Table 1 relating to turbulent flows, four do not meet condition (4), namely those numbered 1, 8, 15, and 22. With the parameter values (3) and taking into account condition (4), i.e., excluding the four rows, formula (1) corresponds to the experimental data in Table 1 for turbulent flows with a root mean square deviation of $\Delta\lambda_{c.k} = \pm 1.71\%$ or, translated to the Chezy coefficient, $\Delta C_{c.k} = \pm 0.86\%$. Considering that, according to our error analysis, the deviations of the experimental values in Table 1 from the true values, due to measurement errors in the experimental setup, can reach 15%, the root mean square deviations presented above indicate a very high degree of correspondence between formula (1) and the parameter values (3) and the actual data.

ISSN: 2350-0328

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Turning now to the results of field studies of turbulent, non-aerated, uniform flows, we note that these were conducted on high-velocity sections of the Mumminabad, Chorshanba, Left Bank Tanhoz, and Right Bank Tanhoz canals in the Kashkadarya region of the Uzbek SSR, which were lined with monolithic concrete. The length of the experimental measurement sections, i.e., the distance between control sections with fixed uniform flow, ranged from 140 to 370 meters. Expansion joints were located every 3 meters and sealed with wooden strips wrapped in tar paper. The overall condition of the concrete surface was "average." The water was clear, and bottom and suspended sediments were practically absent. No aeration was observed.

Data from field geodetic and hydrometric measurements, and some of their processed results, are presented in Table 3. Six series of turbulent, uniform flows were investigated at six different slopes, with the following ranges of variation for key characteristics:

$$Q = 1.041 - 7.424 M^3/c; \quad I = 0.01173 - 0.02917; \quad h_0 = 0.22 - 0.67 \text{ M}$$

$$\mathrm{Re} = (1.88 - 7.67)10^6; \quad \mathrm{Fr} = 2.8\text{-}8.67; \ N = 39.$$

The field data from Table 3 were processed using the same method as the laboratory data from Table 1. Furthermore, the data for slopes of 0.01946 and 0.02107 were considered together with their corresponding average slope value of 0.0203. The results of this processing are presented in Table 2 as coordinate values, which, in turn, were used to construct curves 4 and 5 (Fig. 2). The position of these curves indicates that turbulent, non-aerated, uniform flows in concrete operational channels exhibit the same hydraulic resistance pattern as laboratory concrete flumes. It was not necessary to specifically determine the parameter values of formula (1) for the turbulent flows in concrete channels presented in Table 3, as it turned out that formula (1) corresponds to them with the same parameter values (3) as for the concrete flumes. This correspondence, characterized by a root mean square deviation from the field data of $\Delta\lambda_{c.k} = \pm 3.5\%$ ($\Delta C_{c.k} = \pm 1.8\%$), can be considered exemplary, especially considering that, according to the error theory assessment, the deviations of the field values themselves from the actual values, due to unavoidable errors in field geodetic and hydrometric measurements, can reach $\Delta\lambda = \pm 11.5\%$.

IV.CONCLUSION:

1. Laboratory and field studies of uniform turbulent non-aerated flows in concrete flumes and channels have shown that they exhibit a unique hydraulic resistance law, previously established [1] for similar flows in smooth-walled flumes and precast reinforced concrete channels, which is not accounted for by currently used calculation methods.

2. Formula (1), with the established parameter values (3), accurately represents the actual hydraulic resistance law for uniform turbulent non-aerated flows in concrete flumes and channels, and provides a reliable basis for their calculation within the range of actual data considered in this work.

3. **Validated the applicability of the O.M. Ayvazyan formula** as a reliable tool for describing the hydraulic resistance of turbulent flows in concrete channels. This builds upon prior work and extends the formula's utility to a wider range of practical scenarios.
4. Established specific parameter values (a=0.035; K=-0.000225 м; x=-0.2; z=-1) for the O.M. Ayvazyan formula that accurately represent the observed hydraulic behavior in concrete flumes, significantly improving the precision of hydraulic calculations. These empirically derived parameters provide a valuable resource for hydraulic engineers working with concrete channels.

ISSN: 2350-0328
International Journal of AdvancedResearch in Science, Engineering and Technology
Vol. 12, Issue 2, February 2025

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