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Study of submountain river flow patterns constrained by a combined dam

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Abstract. Great attention around the world is paid to the design and construction of riverbank protection and channel control structures on submountain section of rivers. High slopes (i=0,001÷0,004 and higher), flow kinetics and ability to transport large amount of sediments are the features of submountain section of rivers.
Most of the research in this sphere has been conducted on the study of patterns of flow constrained by transverse structures in valley parts of rivers.
The main goal of this work is to establish the physical picture of flow around a combined dam in submountian river, the through-flow part of which is made of tetrahedrons, as well as to develop a design method for flow velocity field. Formations of two regimes have been established experimentally, i.e. "calm" at $ia<i_{cr}$ and "critical" at $i_a \geq i_{cr}$. These regimes are mainly affected by flow contraction degree n_a, and Froude number Fr.
The presence of the following zones was established: core, intensive turbulent mixing and backflow zones, as well as the affinity of velocity fields in the zone of mixing by Shlihting-Abramovich. Prandtl has realized the task for "calm" regime with the use of integral relationship expressing law of conservation of momentum in the flow, equation for conservation of discharge and differential equation for nonuniform motion of transit flow with the account of tangential turbulent stresses on lateral surfaces. As opposed to the existing solutions, we accounted for the presence of two regions of spreading with different slopes of water surface, horizontal component of fluid weight, nonuniform distribution of velocities in head section, high roughness and the case when sections of target and vertical contraction do not match. Satisfactory results were obtained by comparing theoretical solution and experimental data.

1. Introduction

Erosion control of riverbanks, flood control of cities, towns and riverside land areas is an important task for national economy [1, 2] in the world and in Uzbekistan in particular. Task-oriented scientific research works are being carried out on the improvement of structures, design justification methods and design of flow control structures in rivers [3-9], most of which are done for cases of valley rivers. Most authors have mainly focused on determining the depth of local scouring at the foot of blind dams [10-14].
Meanwhile the submountain sections of rivers have their own particular features, consisting of both morphology and flow hydraulics [15]. River channels are composed of pebbles, gravel and sand, and

the flow is rich in sediment. Flow itself wanders in its own sediment deposits with widely formed floodplain, and riverbanks, which are mostly erodible [16]. Zarafshan, Chirchik, Kashkadarya, Ahangaran and other rivers have the above mentioned features, where slopes range within i=0,001÷0,004.

Flow kinetics is Fr=0,15÷0,5. The studies for these conditions are done for blind transverse dams [17,18], and the study [19] has also covered through-flow structures, while the study for valley rivers showed the operation efficiency of combined dam, consisting of blind and through-flow parts [20-24]. The through-flow part is made of piles driven into channel bed. They are the most capital, their disadvantage is high cost.

We have proposed a combined dam, consisting of blind part from local soil and through-flow part from tetrahedrons, installed at the dam head section.

Experimental studies have been carried out in a laboratory channel with varying slope, the physical picture was explored for flow contracted by a combined dam with tetrahedron through-flow section. The presence of two regimes have been established, i.e. "calm" with n_a<0.3, Fr<0.15, and "critical" with n_a>0.3, Fr>0.15. Theoretical relationships have been obtained for determining velocity field for "calm" regime.

2. Method

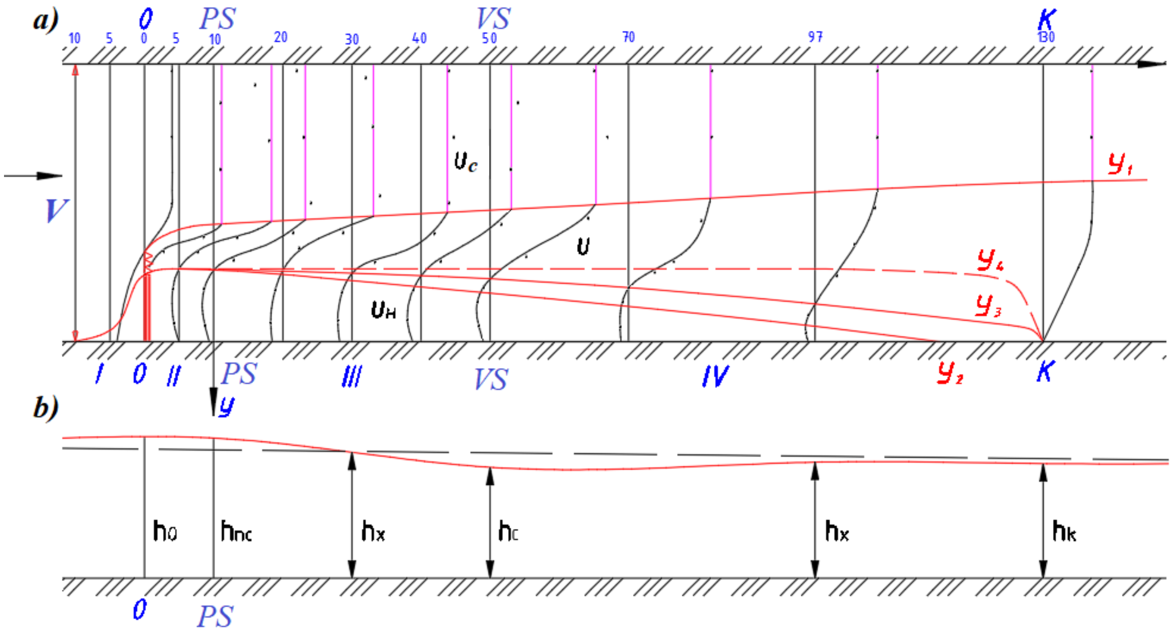
The experimental studies were carried out in laboratory channel with varying slope, with hard bed and 40x75x800 cm dimensions. The studies are done for the following flow and structure characteristics: discharge – 3 to 10 l/sec, total degree of contraction by a combined dam – $n_a=l_a\sin\alpha_a/B$, blind part – $n_b=l_b\sin\alpha_a/B$, through-flow part – $n_t=l_t\sin\alpha_a/B$ (where l_a, l_b, l_t - total length, lengths of blind and through-flow parts, respectively, B – flow width), build-up coefficient for through-flow part - $P = 0{,}3 \div 0{,}65$ $P = W_3/W$ (through-flow part area, total area), dam installation angle - $\alpha_a = 75 \div 90^0$, bed slope - $i_a = 0{,}0001$ до $0{,}004$.

Modelling was carried out according to Froude. Turbulent flow regime was maintained for all experiments. Target task conditions (B⁄h>6) were met. 5x5 cm cells were painted on the channel bottom to ease visual observations. Discharge was measured using Thompson weir. Free water surface was captured with the use of gauge needle. Flow velocities were measured using SANIIRI micro-propeller flowmeter with electronic sensor SISNB-5. Theoretical research used the main regulations of the theory of turbulent jets, spreading in a confined space: flow division into hydraulically homogeneous zones, i.e. zones weakly disturbed core, intensive turbulent mixing and backflow zones.

In order to solve the task, we used the main equations of applied mechanics, law of conservation of momentum in flow, law of conservation of dischare, as well as differential equations for non-uniform motion, written for transit flow with the account of tangential turbulent stresses on lateral surfaces by Prandtl.

3. Results and Discussions

Physical picture of flow around combined dam, through-flow part of which is made of tetrahedrons, have much in common with flow around combined dam with through-flow part made of pile rows [23, 24] for valley rivers, differing both qualitatively and quantitatively. Flow around takes place with formation of damming region between sections A-A and O-O, plane contraction between sections O-O and PS, vertical contraction between sections PS-VS, recovery region between sections VS and K-K and K-K-B-B (Figure.1).



Firuge 1. Comparison of design and experimental velocity diagrams: a) plane, b) longitudian profile

$$Q = 7\ l/sec:\quad \alpha_a = 90^0\ i = 0{,}002:\quad n_a = 0{,}4\quad Fr = 0{,}15$$

«Calm» regime: – - design data, ••• - experimental data

Because of the presence of longitudinal slope $i_a<i_{cr}$, typical for submountain rivers, locations of sections for vertical and plane contraction don't match. Vertical contraction BC also goes along beyond plane contraction section ПС. Beyond vertical contraction section increase of water level takes place all the way to the end of vortex zone and this increase continues within recovery region as well.

It was found that two regimes of contracted flow form at "calm" regime of natural flow ($i_a < i_{cr}$): "calm" regime (when depths exceed critical values) and "critical" (when depth in deformed flow are equal or less than critical values. In the first case the depth of flow in vertical contraction section $h_s < h_{cr}$, where the critical depth of natural flow is.

$$h_{cr} = \sqrt[3]{\frac{\alpha Q^2}{gB^2}} \tag{1}$$

Jet nature of velocity field is preserved when combined dam with tetrahedron through-flow part is flown around and flow-spreading takes place in cocurrent flow. Flow can be considered as the one consisting of a weakly disturbed core, cocurrent flow, intensive turbulent mixing and backflow zones. Depending on the degree of flow contraction $n_д$ and the ration of $n_г$ and n_c, various schemes of flow around can form: when $l_s/l_d \ll 0{,}5$, united zone of intensive turbulent mixing develops, covering the zone of cocurrent flow beyond the through-flow part of the dam, while the operation of the combined dam is almost like for transverse blind dams; when $l_s/l_d > 0{,}5$, two zones of intensive turbulent mixing form, one - between weakly disturbed core and cocurrent flow, the other one – between cocurrent flow and vortex zone. In the work we are dealing with the first case. It has been established that velocity distribution in the zone of intensive turbulent mixing comply with the Shlihting-Abramovich theroretical relationship when head region of the jet is present (Figure.2)

$$\frac{U_y-U}{U_y-Un} = (1-\eta^{1,5})^2 \tag{2}$$

where:

U_s, U_n, U- core velocity, backflow velocity, and velocity in the zone of intensive turbulent mixing, respectively.

$\eta = \frac{y_2 - y_1}{y_2 - y_1} = \frac{y_2 - y}{b}$ - relative ordinate of the point where the velocity is determined (b – the width of the intensive turbulent mixing zone).

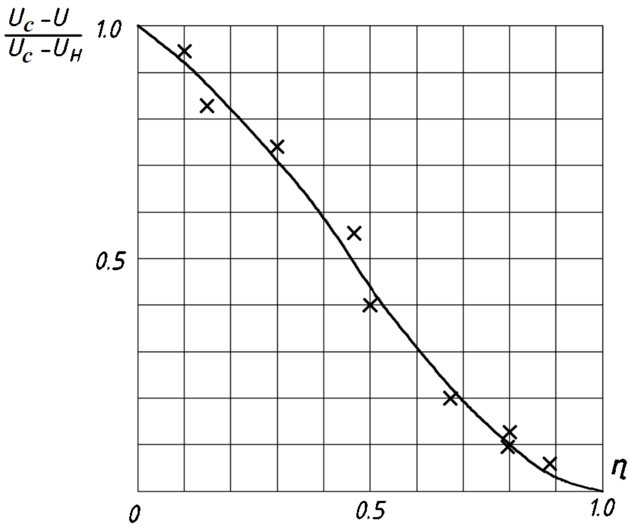


Figure 2. Dimensionless velocity curve for the head section (solid line - theoretical data, x-points – experimental data).

With theoretical research we had to establish changing patterns for velocities in the zone of weakly disturbed core u_{yi}, backflow velocities $u_{\text{н}}$, and the lengths of vortex zone in spreading region l_{V1}, l_{V2} or l_V.
In order to determine velocity change pattern within the third region we used the equation of conservation of impact in flow, which can be written as follows for sections PS and X-X

$$\rho u_{cnc}^2 \text{в}_{cnc}\, h_{nc} + \rho h_{nc} \int_0^{V_c} u^2 dy + \rho u_{\text{н}nc}^2\, h_{nc}(\text{B} - \text{в}_{cnc} - \text{в}_\text{c}) + \frac{\gamma B}{2}(h_{nc}^2) = \tag{3}$$
$$= \rho h_x \cdot \int_0^{\text{в}_{\text{c}1}+\text{в}} u^2 dy + \rho u_{\text{н}}^2 h_x(\text{B} - \text{в}_{\text{c}1} - \text{в}_1) + \rho \int_0^x \int_0^{\text{в}_{\text{c}1}+\text{в}_1} \frac{\lambda u^2}{2} dy dx + \frac{\gamma \text{B}}{2} h_x^2 - \frac{\gamma}{2}(h_{nc} + h_x)\text{B} i_\text{d} x$$

for which the flow depth for section X-X is determined as follows:

$$h_x = h_{nc} + i_\text{d} x - ix = h_{nc} - x(i - i_\text{d}) = h_{nc} + Jx$$

$\mathcal{J} = i_\text{a} - i,\ \ \frac{dh}{dx} = \mathcal{J} = \frac{h_{nc} - h_x}{l_{\text{в}1}}$

By integrating (3) with the account of (1) we get integral relationship, which can be solved to get the following relationship to determined velocities in the weakly disturbed core.

$$(\overline{U}_{ci})^2 = \frac{F_{1i}}{F_{2i}}\left(\overline{h}_i\right)^{1-\frac{\lambda}{2\mathcal{J}}} - \frac{P_i}{F_{2i}}\left[\left(\overline{h}_i\right)^{1+\frac{\lambda}{2\mathcal{J}}} - \left(\overline{h}_i\right)^{-1}\right] - \frac{i_\text{a} \cdot \Psi}{2(1 - n_\text{b} - n_\text{c}) F_{2i}\, F_{ri}} \tag{4}$$

While determining the velocities in the weakly disturbed core:
For region III we need to assume the following

$\overline{U}_{ci} = \overline{U}_\text{c} = \frac{U_{\text{c}1}}{U_{\text{спс}}};\quad F_{1i} = \overline{\text{в}}_{\text{спс}} + 0{,}416\overline{\text{в}}_\text{c} \quad F_{2i} = \overline{\text{в}}_{\text{c}1} + 0{,}416\overline{\text{в}}_1 \quad \overline{h}_i = h_{nc}/h_x$

$$P_i = \frac{2\mathcal{J}}{(4\mathcal{J} + \lambda)(1 - n_\text{г} - n_\text{c}) Fr_{nc}} \quad F_{ri} = F_{r_{nc}} = U_{\text{спс}}^2 / g h_{nc} \tag{5}$$

$\Psi = \frac{\xi^2}{\overline{h}_x \overline{h}_{nc}};\ \xi = x/b_0;\ x$ is measured from PS to VS or from o to l_{b1} $\overline{h}_x = h_x/b_0$ $\overline{h}_{nc} = h_{nc}/b_0$
$n_\text{b} = l_\text{b} sin\alpha_\text{a}/\text{B} \quad n_\text{c} = l_\text{b} sin\alpha_\text{a}/\text{B}$

For region IV we need to assume the following:
$\bar{U}_{ci} = \bar{U}_{c2} = U_{c2}/U_{\text{свс}}$; $F_{1i} = \bar{\text{в}}_{\text{свс}} + 0{,}416\bar{\text{в}}_{\text{c}}$; $F_{2i} = \bar{\text{в}}_{\text{c2}} + 0{,}416\bar{\text{в}}_2$; $h_i = h_{\text{c}}/h_x$
$P_i = \frac{2\mathcal{J}}{(4\mathcal{J}+\lambda)(1-n_{\text{b}}-n_{\text{c}})Fr_c}$; $F_{ri} = F_{r_c} = \frac{U^2_{\text{свс}}}{gh_{\text{c}}}$; $\Psi = \frac{\xi^2}{\bar{h}_x\bar{h}_c}$; $\xi = x/b_0$; x is measured from VS to K-K or from o to l_{b2} $\mathcal{J} = i_{\text{a}} + i_{\text{об}}$ $h_x = h_c + \mathcal{J}_x = h_c + (i_{\text{a}} + i_{\text{ob}})x$ mean value in the region $i_{\text{ob}} = \frac{h_{\text{b}}-h_{\text{c}}}{l_{\text{в2}}}$

Backflow velocities in vortex zone are determined from the equation of conservation of discharge, written for the above mentioned regions and sections PS and X-X which have the following form

$$U_{cnc}b_{cnc}h_{nc} + h_{nc}\int_0^{\text{B}_c} udy + U_{\text{нnc}}h_{nc}(\text{B} - b_{cnc} - b_c) =$$
$$U_{c1}b_{c1}h_x + h_x\int_0^{\text{B}_1} udy + U_{\text{н}}h_x(\text{B} - b_{c1} - b_1) \quad (6, 7)$$

By integrating with the account of (2) we obtained the equation for determining backflow velocities

$$m_i = \frac{M_i\bar{\theta}_i - T_i}{\frac{1}{(1-n_{\Gamma}-n_{\text{c}})} + T_i} \quad (8)$$

For region II

$$M_i = \frac{U_{\text{cnc}}}{U_{\text{c1}}} \cdot \frac{h_{\text{nc}}}{h_{\text{nc}} + \mathcal{J}x}$$
$$\bar{\theta}_i = (1 - m_{nc})(\bar{b}_{\text{cnc}} + 0{,}55\bar{b}_{\text{c}}) + \frac{m_{nc}}{(1-n_{\text{d}}-n_{\text{c}})} \quad (9)$$

$T_i = \bar{b}_{\text{c1}} + 0{,}55\bar{b}_1$ $m_i = m_{nc} = U_{\text{н}nc}/U_{cnc}$ $\mathcal{J} = i_{\text{a}} - i$
For region IV

$$M_i = \frac{U_{\text{свс}}}{U_{\text{c2}}} \cdot \frac{h_{\text{c}}}{h_{\text{c}}+\mathcal{J}x} \qquad \bar{\theta}_i = (1 - m_{\text{вс}})(\bar{b}_{\text{свс}} + 0{,}55\bar{b}_{\text{c}}) + \frac{m_{\text{нвс}}}{(1-n_{\text{b}}-n_{\text{c}})} \quad (10)$$

$\mathcal{J} = i_{\text{a}} + i_{\text{ob}}$ $i_{\text{ob}} = \frac{h_{\text{b}}-h_{\text{c}}}{l_{\text{в2}}}$

The length of vortex zone can be determined from the equation of non-uniform motion, written with the account tangential turbulent stresses on lateral surfaces

$$i = \frac{\alpha Q^2}{g} \cdot \frac{1}{\omega^3} \cdot \frac{\partial \omega}{\partial x} - \frac{\alpha Q^2}{g} \cdot \frac{B_x}{\omega^3} \cdot \frac{\partial h}{\partial x} + \frac{Q^2\lambda}{\omega^2 2gh} + \frac{K^2Q^2}{g\omega^2 b}(1 - m^2) \quad (11)$$

where
ω – cross section area of transit flow;
K – Carman's constant;
α - correction factor for kinetic energy.
In the integration we assumed that
$i = i_{\text{cr}} = \frac{h_{nc}-h_{\text{c}}}{l_{b1}}$; $i_{\text{ob}} = \frac{h_{\text{b}}-h_{\text{c}}}{l_{b2}}$; $\frac{dh}{dl} = \mathcal{J} = const$
Integration order by regions stay the same [6,7,20,24], therefore the final form is written as follows

$$l_{b1} = \frac{A}{E} ln \frac{C_1}{C_2}\sqrt{\frac{DC_2^2+E}{DC_1^2+E}} \quad (12)$$

For the third region
$l_{bi} = l_{b1}$; $A = 2\alpha Q^2 h_{\text{m}}$; $D = -2gi_{\text{m}}h_{\text{m}}$;

$$E = Q^2\left(\frac{\lambda_{\text{b}}h_{\text{m}}}{B_{\text{m}}} + \lambda_{\text{a}} + 2{,}88k^2\frac{h_{\text{m}}}{b_{\text{m}}} - 4\alpha\mathcal{J}\right) \quad (13)$$

$h_{\text{m}} = \frac{h_{nc}-h_{\text{c}}}{2}$; $b_{\text{m}} = \frac{b_{1nc}-b_{1\text{вс}}}{2}$; $b_{1x} = b_{1nc} + 0{,}27x$; $B_{\text{m}} = \frac{b_{\text{tвс}}+b_{\text{tnc}}}{2}$; $c_1 = b_{\text{tвс}}$

$$c_2 = b_{tnc} \quad \alpha = 1{,}15$$

For the fourth region
$l_{bi} = l_{b2;}$ $D = -2gi_{\text{об}}h_{\text{m}}$; $h_{\text{m}} = \frac{h_c+h_{\text{b}}}{2}$; $b_{\text{m}} = \frac{b_{1\text{вс}}+b_{1x}}{2}$; $B_{\text{m}} = \frac{b_{\text{tвс}}+B}{2}$;

$$\mathcal{J} = i_a + i_{ob} \quad b_{1x} = b_{1nc} + 0{,}27x \quad \alpha = 1{,}35 \quad (14)$$

λ_a, λ_b- hydraulic friction coefficients for channel bed and channel bank, respectively; k- Carman's constant, which is equal to 0.21.

The flow width to depth ratio B⁄H>6; discharge Q=3.0: 5.0: 7.0 l⁄s; turbulent regime is maintained in all experiments. As the result of processing and summarization of the initial experimental material, we defined a number of specific section and regions of flow, contracted by a transverse dam.
The flow consists of typical regions: damming and upstream swirling, plane and vertical contraction, turbulent mixing, backflow zones.
Transverse blind channel control structures are widely used to control river channels. Their main advantage compared to longitudinal dams is that they can protect riverbank at the distance of 2 to 4 times the length of transverse dam. Among their disadvantages, we can point out large depths of local scouring at the head of the dam, which requires large volume of fixing them to the bottom. Through-flow structures have the danger to be flown around at their root, but their local scouring depth is significantly smaller. Combined dams have the combination of advantages from both those structures. The existing structures, whose through-flow sections are mainly of a pile type, require huge material expenses. We proposed a combined dam, whose blind section is made of local soil and the through-flow part is made of precast tetrahedrons. In order to explore the physical picture, experimental studies were carried, applicable to submountain river conditions with slopes $i = 0.001 \div 0.004$, flow kinetics $\mathrm{Fr} > 0.15$, through-flow part build-up coefficient $\mathrm{P} = 0.3 \div 0.65$, contraction degree $n_a < 0.5$. Formation of two flow around regimes was determined: "calm", that is when $n_a < 0.3$, $\mathrm{Fr} < 0.15$, "critical", that is when $n_a > 0.3$, $\mathrm{Fr} > 0.15$. It was determined that flow around of the combined dam with tetrahedron through-flow part has the jet nature. Velocithyy distributions in the zone of intensive turbulent mixing are affine and comply with Shlihting-Abramovich theoretical relationship. We have developed design method for velocity field of flow, contracted by combined dam with tetrahedron through-flow part for submountain parts of rivers. The task is accomplished for the first "calm" regime with the use of integrated ratio, characterizing the law of conservation of momentum, equations of conservation of discharge and non-uniform motion, written with the account of tangential turbulent stresses on lateral surfaces of vortex by Prandtl. Design relationships are obtained to determine velocity change in weakly disturbed core U_{ci}, back flow currents U_n and the lengths of vortex zones in the region of spreading $l_{\text{в}1}, l_{\text{в}2}$. Direct calculations and their comparisons with experimental data showed that the theoretically obtained results are accurate.

4. Conclusions

1. Physical picture of flow around of a combined dam with tetrahedron through-flow part qualitatively and quantitatively differ from the existing ones of pile and hydraulic barrier type.
2. The flow has jet nature, the flow around occurs in presence of concurrent and back flows.
3. Velocity distribution in the zone of intensive turbulent mixing complies with Shlihting-Abramovich theoretical relationship.
4. Relationships were obtained theoretically to determine velocities in the weakly disturbed core, backflow, and plane dimensions of flow spreading. They were used to determine velocity field, comparing them with non-erosive velocities, we can establish scouring boundaries. Knowing the plane dimensions of vortex zones, we can set distances between the structures within system.
5. Comparison of the design and experimental data shows their applicability, since the maximum deviation does not exceed 8%.

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