

Generation of artificial transverse circulation in an open channel flow by submerged vanes

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ABSTRACT

Introduction. In this article, we describe a method for sediment control in damless water intake hydraulic units consisting in artificial transverse circulation (ATC) generated by redistributing specific water flow rates in the cross-section of the supply channel. One of the simplest and most effective anti-sediment elements working according to this principle is the submerged vane (SV). The intensity of the ATC formed in the flow depends on the flow regime and the planned-geometric characteristics of the vanes. Available recommendations on the selection of the rational characteristics of SV under the conditions of river damless water intake appear to be contradictory, thus requiring clarification. This study is aimed at examining the interaction between SV and a model flow without water trapping under various planned-geometric characteristics of the vane and experimental hydraulic regimes of its work using a physical model of the erosion-resistant channel. In addition, we set out to assess the effect of essential parameters on the intensity of the ATC generated in the flow.

Materials and methods. This research was based on physical modelling hydraulic studies and theoretical calculations. Five hydraulic modes of vane operation with different planned-geometric characteristics were studied using a physical model of the erosion-resistant channel. Multiple regression analysis of the obtained experimental data was carried out.

Results. The results of laboratory hydraulic studies on the SV operating conditions are presented. Experimental dependencies characterising the intensity of the ATC generated in the flow are plotted. A multiple regression equation is derived for the amount of the data obtained.

Conclusions. It is established that the relative height of the vane and its angle to the side of the flume (coastline) has a significant effect on the intensity of the generated ATC. It is experimentally confirmed for the first time that SV shows little efficiency in high water horizons in terms of in-flow ATC generation.

KEYWORDS: water intake units, channel sediments, artificial transverse circulation, submerged vane, regression analysis

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Возбуждение искусственной поперечной циркуляции в открытом русле косонаправленными донными циркуляционными порогами

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АННОТАЦИЯ

Введение. Рассмотрен способ борьбы с наносами на бесплотинных водозаборных гидроузлах в виде искусственной поперечной циркуляции (ИПЦ), возбуждаемой в потоке перераспределением удельных расходов воды по ширине подводящего русла. Одним из наиболее простых и эффективных наносозащитных элементов, работающих по данному принципу, является косонаправленный донный циркуляционный порог (КДЦП). Интенсивность формируемой в потоке ИПЦ зависит от режима водотока и плано-геометрических характеристик донной преграды. Имеющиеся рекомендации по выбору рациональных характеристик КДЦП для условий бесплотинного забора воды из рек носят противоречивый характер и требуют уточнения. Цель исследования — изучение характера взаимодействия КДЦП с модельным потоком без водоотделения при различных плано-геометрических характеристиках порога и экспери-

ментальных гидравлических режимах его работы на физической модели с неразмываемым руслом, а также оценка степени влияния определяющих параметров на интенсивность возбуждаемой в потоке ИПЦ.

Материалы и методы. Использованы физические модельные гидравлические исследования, теоретические расчеты. Изучены пять гидравлических режимов работы донных преград с различными планово-геометрическими характеристиками на физической модели с неразмываемым руслом. Проведен множественный регрессионный анализ полученных экспериментальных данных.

Результаты. Представлены результаты лабораторных гидравлических исследований условий работы КДЦП. Разработаны экспериментальные графические зависимости, характеризующие интенсивность возбуждаемой в потоке ИПЦ. Составлено уравнение множественной регрессии в объеме полученных материалов.

Выводы. Установлено определяющее влияние на интенсивность возбуждаемой ИПЦ относительной высоты порога и угла установки преграды к борту лотка (береговой линии). Экспериментально доказана неэффективность работы КДЦП в условиях высоких горизонтов воды с точки зрения возбуждения в потоке ИПЦ, что не нашло отражения в работах предшествующих исследователей.

КЛЮЧЕВЫЕ СЛОВА: водозаборные гидроузлы, русловые наносы, искусственная поперечная циркуляция, косонаправленный донный циркуляционный порог, регрессионный анализ

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INTRODUCTION

One of the most difficult problems in ensuring a guaranteed supply of river water of the required quality to irrigation and drainage systems consists in the struggle against the sediment capture by water intake hydraulic units, primarily bottom ones [1–7]. In order to solve this problem at a design stage, during operation or reconstruction, various anti-sediment systems or their individual elements are included in the composition of the layout schemes for water intake hydraulic units. The experience gained in operating low-pressure water intakes on rivers of the mountain foothill zone transporting a large amount of sediment has shown the effectiveness of applying protective systems and elements redistributing the specific water duty along the cross-section of the supply channel due to artificial transverse circulation (ATC) generated in the water flow [8, 9].

In the domestic hydraulic engineering science, theoretical foundations of ATC generating in an open channel were laid by R.Zh. Zhulaev, who, on the basis of a set of theoretical and experimental studies, showed that any displacement of the dynamic axis of the flow, including one due to the redistribution of specific discharge along the cross-section of the supply channel, leads to its stratification and, hence, to the appearance of transverse movement of water masses in it (transverse flow circulation) [10, 11].

A critical analysis of available publications showed that the submerged vane (SV) is one of the most effective and simplest in both constructive and operational terms of a anti-sediment element [12, 13]. This element

received its name in the works of foreign researchers [14–18]. Such a submerged barrier located at a certain β angle to the coastline generates artificial transverse circulation in the flow by providing an effective redistribution of specific water flow rates along the cross-section of the supply channel. In the area of the protected water intake structure, straight after the specific consumption curve, the sediment curve is also transformed in the direction necessary for practice. The criterion for assessing the intensity of the generated ATC in the supply channel with a width of B is presented as the relative value for the displacement of the flow dynamic axis, $\lambda = f/B$, where f is the difference in the position of the centres of mass of the unit discharge curves in the cross-section and in the area outside the influence zone of the vane.

G.V. Sobolin [12] found that the ATC intensity is affected by the β vane angle to the coastline, $P' = P/H_0$ relative vane height (where P is the average vane height, H_0 is the water depth of the domestic channel), i slope of the upper edge of the vane from its base (root) near the shore to the end of the vane, as well as the $n = b_d/B = l \sin \beta / B$ flow restriction (where l is the geometric length of the vane) and V_0 average flow rate, when approaching the water intake.

In accordance to the recommendations of G.V. Sobolin and I.K. Rudakov, submerged vanes should be straightforward, mounted at $\beta = 15...30^\circ$ angle to the flow, with the $2B$ length, restricting the channel by 60...80 % ($n = 0.6...0.8$) and with $i = 0.005...0.20$ longitudinal slope of the upper edge of the vanes to the river bed. It should be noted that these recommendations are more true for the vane operation in the composition of

According to V.S. Bondarenko, under the conditions of damless water intake at $\alpha \leq 0.2$, it is advisable to increase the β vane angle up to $40...50^\circ$, while the n restriction value should be determined for specific conditions of water intake using the recommendations given by A.S. Obrazovskiy [19].

MATERIALS AND METHODS

Our research aim was two-fold:

- a study of the interaction between a SV and a model flow without lateral intakes for various planned, geometric characteristics of the vanes and hydraulic modes of its operation using a physical fixed-bed model;
- an assessment of the effect of the P' relative vane height, the n channel constriction, the i slope of the upper edge of the vane, as well as the V' relative value of

To this end, the following objectives were addressed:

- The studies were performed using an experimental installation described in (Fig. 1) using the facilities of the Hydraulics Laboratory of Culverts at the Department of Hydrotechnical Structures at the Russian State Agrarian University — Moscow Timiryazev Agricultural Academy.

Considering the need to compare the results with experimental data of other authors, as well as the possibilities of the experimental installation and the available data on the effective range of the relative height of the vanes ($P' = 0.25...0.5$) [2, 13, 19], five operating modes were studied for each type of vane (Table 1).

Vanes were manufactured of organic glass with a high degree of accuracy with their planned and ge-

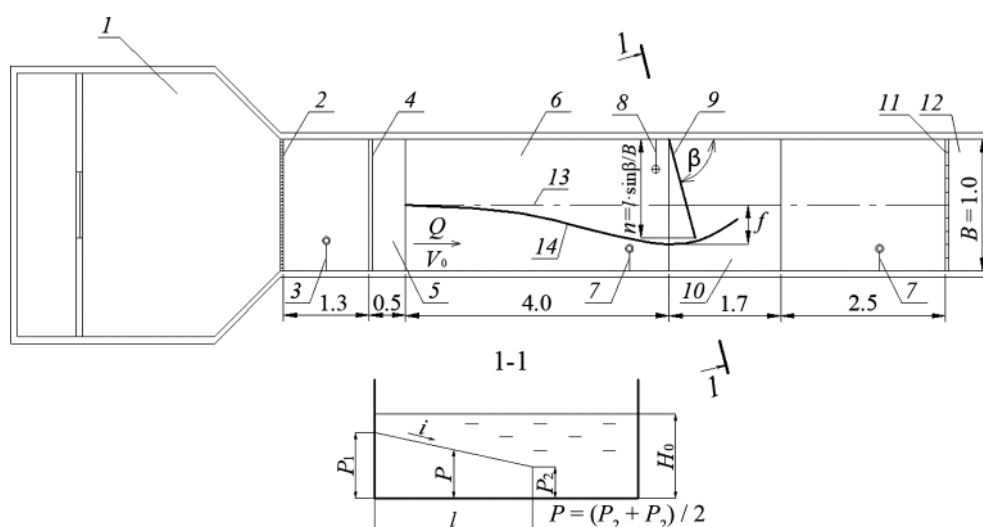


Fig. 1. Schematic view of the experimental installation: 1 — drain tank; 2 — diffusion grid; 3 — transversal scale; 4 — measuring spillway; 5 — diffusion device; 6 — hydraulic flume; 7 — moving transversal scale; 8 — miniflowmeter; 9 — submerged vane; 10 — vane installation area; 11 — louvre damper; 12 — downshaft; 13 — dynamic axis of the flow before generation of the ATC; 14 — dynamic axis of the flow after generation of the ATC (in meters)

Table 1. Experimental hydraulic threshold (vane) operation modes

Experimental mode	P , m	H_0 , m	$P' = P/H_0$	V_0 , m/s	$V' = V_0/V_{0,\max}$	Q , $\text{m}^3/\text{s} \cdot 10^{-3}$
1	0.06 ($P_1 = 0.07$, $P_2 = 0.05$)	0.12	0.5	0.25	0.833	30
2		0.15	0.4	0.20	0.667	30
3		0.15	0.4	0.25	0.833	37.5
4		0.15	0.4	0.30 ($V_{0,\max}$)	1	45
5		0.15	0.3	0.25	0.833	50

ometric characteristics determined considering the intended volume of research. The model studied the hydraulic operating conditions of the SV located at $\beta = 15...75^\circ$ angles to the side of the flume (β increment step is 15°). The $n = 0.2...0.8$ range of flow restriction was applied (n increment step is 0.15), reflected in $n = 0.2$ and $n = 0.35$ values regarding the capabilities of the laboratory installation with $\beta = 15^\circ$. Under the experimental conditions, the i slope of the upper edge of the vane varied from 0.0125 ($n = 0.8$; $\beta = 30^\circ$) to 0.0966 ($n = 0.2$; $\beta = 75^\circ$). The P average height of the vane comprised 6 cm, while the P' relative height of the vanes possessed values of 0.3; 0.4; 0.5.

To assess the intensity of the ATC generated in the flow, for each design case, a curve of specific discharge in the cross-section was constructed and the $\lambda = f/B$ relative displacement of the dynamic axis of the flow was determined. Plotting of the specific discharge curves was carried out for 11 verticals in the cross-section with a step of 10 cm across the width of the flume on the basis of flow velocities obtained by a miniflowmeter (for $n = 0.35$ and $n = 0.65$, at a distance of 35 and 65 cm from the bottom of the vane, respectively, an additional 12th measuring vertical was introduced). Depths at design points were measured using moving transversal scales.

RESULTS

Figure 2 presents dependences plotted using the results of laboratory experiments characterising the intensity of the transverse circulation generated in the flow by vanes of various structural types. An analysis and generalisation of the results of laboratory studies showed that both a decrease in the β angle and a decrease in the P' relative height of the vane lead to a decrease in the ATC intensity.

An important circumstance is the inefficiency of submerged vanes established through laboratory studies with the $\beta = 15...60^\circ$ installation angle in conditions of high water horizons from the point of view of the ATC formation in the flow. In the general case, for SV with β angles of the indicated range at values of $P' \leq 0.35$, the artificial transverse circulation of the flow changes

direction to opposite (towards the part of the channel blocked by the vane).

In order to identify the actual degree of influence for each of the essential parameters on the ATC generation conditions, a multiple regression analysis was applied.

For a reliable assessment of the degree of influence of the P' relative vane height, following parameters were required at the initial stages to exclude multicollinear variables from the multiple regression equation: V' relative value of the average flow velocity, n flow restriction, i slope of the upper edge of the vane and the β angle of its installation to the side of the flume. For this, a correlation matrix was compiled with the analysis resulted in the following:

1) the velocity mode of the main flow demonstrate no effect on the nature of the phenomena studied, since the correlation coefficient between the λ and V' values is equal to 0.006;

2) a weak correlation between λ and i (–0.150 correlation coefficient) was noted and multicollinearity in pairs of $i - n$ and $i - \beta$ essential parameters was revealed; a close correlation is observed between the value of λ and the β angle of the vane.

The multiple regression equation in coded factors takes on the following form:

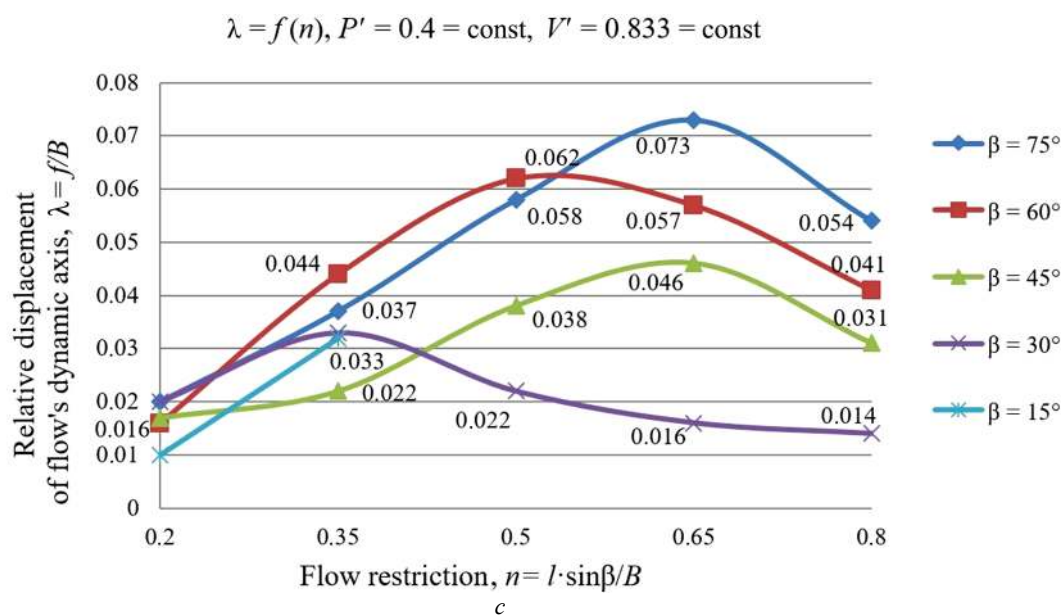
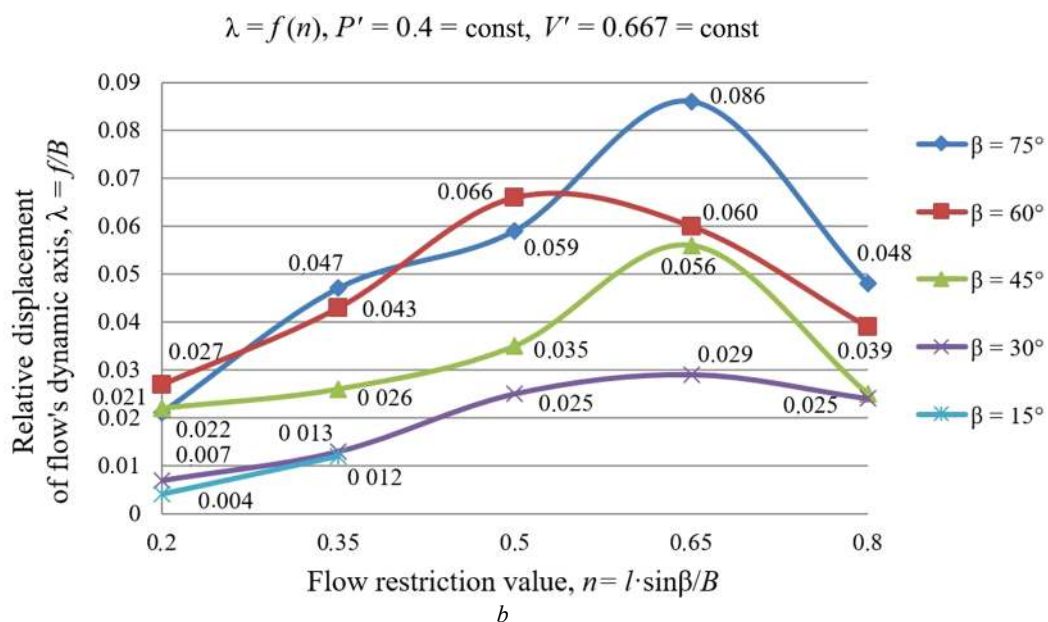
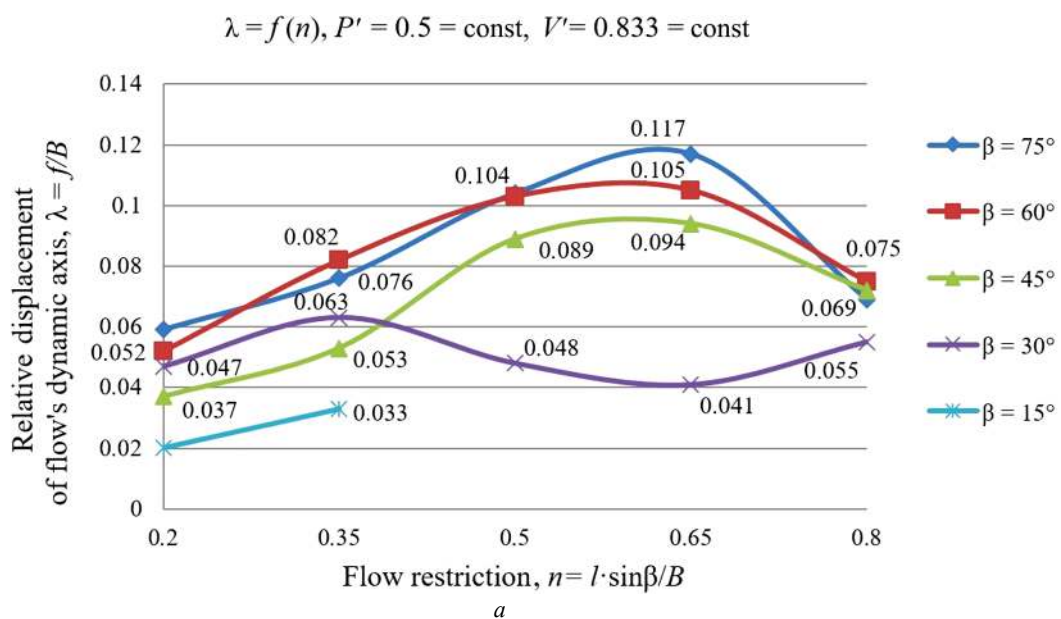
$$\lambda = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3, \quad (1)$$

where the x_1 independent variables are the relative height of the vane P' , x_2 is the n flow restriction and x_3 is the β angle of installation of the vane to the side of the flume. The methodology for conducting multiple regression analysis is described in detail in [9].

For equation (1), the values of the β_0 free term and the β_1 , β_2 and β_3 coefficients before the independent variables are as follows:

$$\lambda = 0.0375 + 0.0369x_1 + 0.009x_2 + 0.0181x_3. \quad (2)$$

Statistical estimates (multiple correlation coefficient and determination coefficient is $R = 0.8411$ and $R^2 = 0.7075$, respectively) demonstrated the high quality of the multiple regression equation. The calculated adjusted determination coefficient turned out to



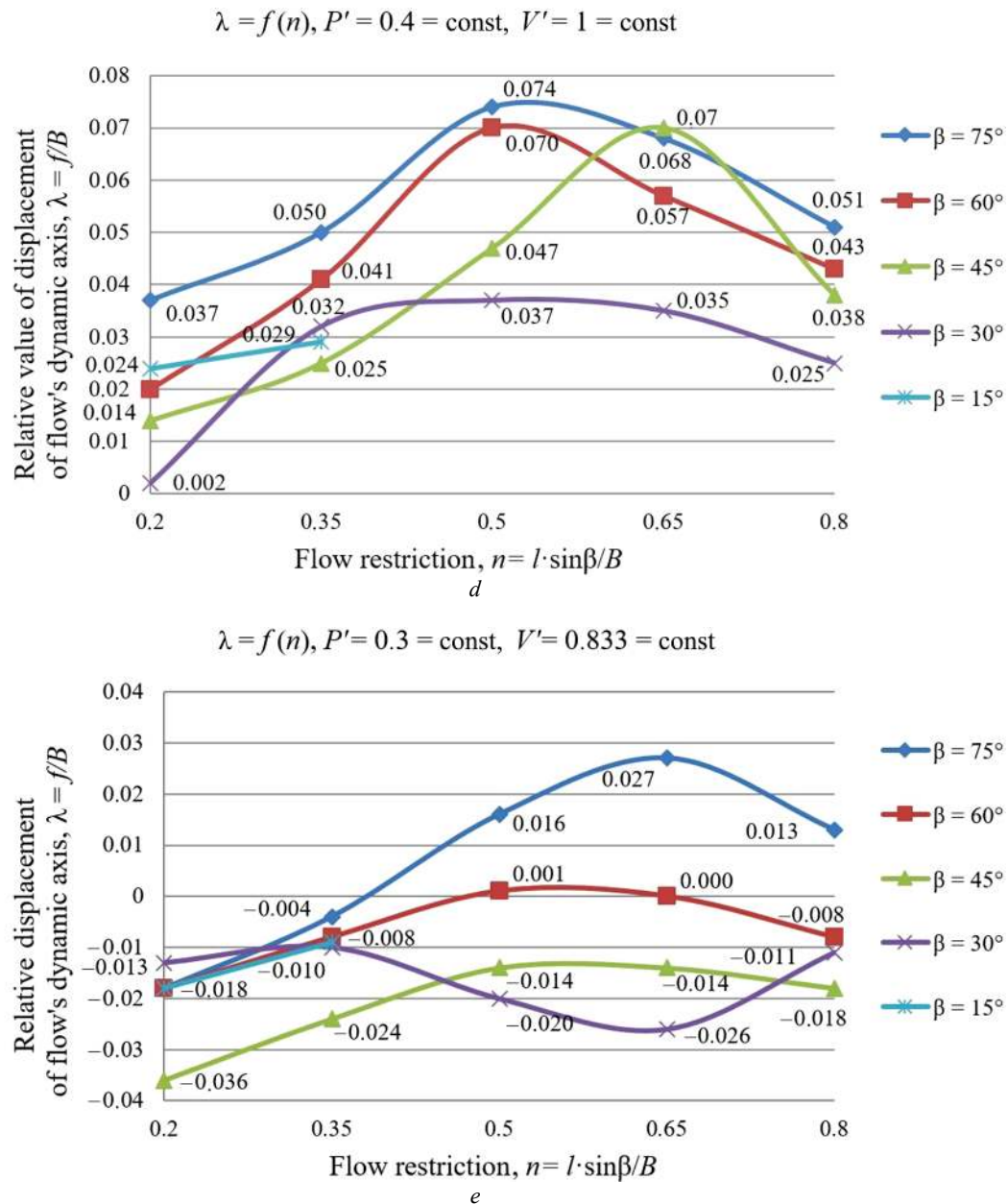


Fig. 2. Experimental dependences of flow restriction on the relative displacement of the flow dynamic axis, $\lambda = f(n)$: *a* — mode No. 1; *b* — mode No. 2; *c* — mode No. 3; *d* — mode No. 4; *e* — mode No. 5

$be = 0.6992$. The significance of the equation by the Fisher test comprises $F = 85.4497 > 2.6903$ ($p < 0.05$). The coefficients for all independent variables are found to be statistically significant ($p < 0.05$), and the relationship is direct. The most significant coefficients for the variables were x_1 and x_3 ($p < 0.0001$). Therefore, the main influence on the intensity of the generated ATC is exerted by the P' relative height of the vane and the β angle of installation of the. Moreover, with increasing values of P' and β , the value of λ also increases, indicating the formation of a more stable transverse circulation in the flow.

DISCUSSION AND CONCLUSIONS

1. Regardless of its planned and geometric characteristics, the submerged vanes installed in the flow permit the redistribution of specific discharge in the cross-section of the supply channel, which is a necessary and sufficient condition for the generation of ATC in the flow.

2. A decrease in the β angle of the vane leads to a decrease in the intensity of the ATC. An important circumstance is the inefficiency of vanes established during laboratory studies with the $\beta = 15 \dots 60^\circ$ installa-

tion angle under the conditions of high water horizons in terms of the ATC formation in the flow. In the most general case, for vanes with β angles from the indicated range, at values of $P' \leq 0.35$, the artificial transverse circulation of the flow changes direction to opposite (towards the part of the channel blocked by the vane).

3. The results of the performed multiple regression analysis indicate the actual absence of the influence of the average flow rate on the ATC generation conditions. The P' relative height of the vane and the β angle of

installation are of decisive importance: increased P' and β values result in an increased λ value, which indicates the formation of a more stable transverse circulation in the flow.

Future research should address the development and study of effective sediment protective devices as part of water intakes on rivers with sharply varying levels, as well as the study of channel processes in the upper and lower pools of water intakes, which feature submerged vanes in their design.

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