Calculation of Dangerous Jumping Flows’ Energy Beyond the Dams of Hydropower Station

Alexander Solovyev¹, Dmitry Solovyev², and Liubov Shilova¹

¹ Moscow State Academy of Water Transport, 117105, 2/1 Novodanilovskaya nab., Moscow, Russian Federation
² Shirshov Institute of Oceanology, Russian Academy of Sciences, 117997 Nahimovskiy prospects 36, Moscow, Russian Federation

shilovala@mgsu.ru

Abstract. The problem of reducing the energy of hydraulic jumps arising beyond the hydropower station dams is considered. A relationship is obtained for calculating the specific mechanical energy of the jump, taking into account the exchange of water masses between the roller and the transit flow. A comparison with the experimental data and the proposal of practical use is made.

1. Introduction

An analysis of domestic and international experience shows that the problem of reducing the energy of hydraulic jumping flows beyond the dams of hydropower stations is relevant and requires additional study [1-4]. This is due to the fact that the precise definition of energy and dynamic effects of catastrophically dangerous jumping rises in water levels on river channels and the coastal building infrastructure is a prerequisite for making informed decisions ensuring the normal and safe operation of water bodies and land-based onshore facilities [5].

In this regard, this paper aims to analyze current approaches to estimating the energy effects of hydraulic jumps on river infrastructure facilities and to consider the calculated ratios used in the analysis of hydrodynamically unfavourable situations associated with sharp rises in water levels in river currents. To achieve this goal, the following tasks were set:

1. to study the existing methods of carrying out calculations to determine the energy of jumping river flows;
2. to obtain a ratio for calculating the energy loss in a hydraulic jump using the equations of motion of open flows with a variable flow rate;
3. to compare theoretical formulas and experimental data obtained in jumping currents with experimental models in laboratory hydraulic channels.

2. The method of calculating the energy loss in a hydraulic jump

When the fluid flows unevenly in river flows beyond the dams of hydropower station, when the water depth is less than critical values and less than the normal depth, there is a sharp rise in the free surface of the currents in the form of a depth jump [6]. The rise of water is accompanied by a cap of foamed water in the form of a so-called drum. Assuming that the movement in a jump is determined by the flow
of momentum over a roller’s cross section for calculating the change in specific mechanical energy is \( \Delta E \), the formula obtained in which the energy loss is determined through the height of the jump normalized to the conjugate depths at the boundaries of the jump [1].

\[
\Delta E = \left( \frac{\alpha V_1^2}{2g} + h_2 \right) - \left( \frac{\alpha V_2^2}{2g} + h_2 \right) = \frac{(h_2 - h_1)^3}{4h_2h_1}
\]  

(1)

Here, \( h_1, h_2 \) are the first and the second conjugate depth of the hydraulic jump; \( V_1, V_2 \) are speeds; \( \alpha \) is a kinetic energy coefficient.

For practical calculations, a series of semi-empirical formulas are proposed, in which the jump energy is expressed through various combinations of dependencies on the conjugate depths with limitations in use according to the conditions of applicability [7]. Comparative estimates of experimental data and calculations using the formula (1) and semi-empirical relationships are an insignificant discrepancy, especially for the most intense current jumps. Meanwhile, observations of the jump indicate that in the movement of water in the drum, which is reciprocating in nature, there is a movement of particles in the direction opposite to the transit flow with the transition of liquid masses from the main flow into the drum. In the overwhelming majority of cases, calculations based on semi-empirical relations, as well as when calculating the magnitude of energy losses by the formula (1), proceed from the assumption that the movement in a jump occurs with saving the flow. This means that when calculating the energy of the jump, the rejection of neglecting the change in flow rate along the flow path can be productive to achieve more accurate energy dependences on the height of the rise of the depths in the jump current.

The equation was integrated with a variable flow \( dq/q \) between the section corresponding to the critical depth and the section with the current depth [8] to obtain a calculated ratio for the jump energy:

\[
\Delta E = \int_{q_1}^{q_2} \frac{\alpha V^2 dq}{gq}
\]  

(2)

The jump function with linear depth dependence on the flow is used for converting the integrand expression to one variable - water depth in the jump. After integration, the following relation for calculating the loss of specific mechanical energy is obtained:

\[
\Delta E = \frac{(h_1 + h_2)^2 (h_2 - h_1)}{4\phi h_1 h_2}
\]  

(3)

3. Results and discussions

For comparison the results of the calculation and the experimental data for energy losses obtained in various experiments with modelling of hydraulic jumps, including experimental laboratory installations, are shown in the Fig. 1.
Figure 1. The dependence of the loss of specific mechanical energy $\Delta E$ in hydraulic jumping currents on the flow rate $q$ in experimental and calculated data. 1 - calculation by the formula (3); 2 - calculation by the formula (1); ○ - experiments [3]; ● - data of laboratory measurements of the authors; ★ - experiments [8].

4. Conclusions

According to the analysis of observations of the jumping flows’ energy, the need to take into account additional flow from the transit flow, which feeds the roller motion for precise estimates of hydraulic phenomena that are dynamically dangerous for hydraulic structures, is established.

An exact relationship is given for determining the mechanical energy of a hydraulic jump, obtained by integrating the equation of motion of water flows with a variable flow rate, which makes it possible to eliminate contradictions between existing theories and experimental data.

The obtained analytical correlations make it possible to increase the accuracy of the prognostic estimates of dangerous sharp rises of water behind the dams of hydraulic structures, which can be used in making management decisions necessary to eliminate adverse environmental consequences.

Acknowledgement(s)

This project was supported by the Russian Ministry of Science and Higher Education (agreement No. 075-02-2018-189 (14.616.21.0102), project ID RFMEFI61618X0102).
References

[1] Y. Kim, G. Choi, H. Park, and S. Byeon, “Hydraulic jump and energy dissipation with sluice gate,” Water (Switzerland), vol. 7, no. 9, pp. 5115–5133, 2015.

[2] W. Hager, “Energy dissipators and hydraulic jump,” 2013.

[3] E. I. Romanenko and MN Chernichko, “Studies of a hydraulic jump as a water meter,” Kharkiv National Bulletin Automobile and Highway University, no. 37, pp. 91–93, 2007.

[4] H. Chanson, “Hydraulics of stepped chutes and spillways,” 2002.

[5] JR Wyrick and GB Pasternack, “Modeling energy dissipation at the river steps,” J. Geophys. Res. vol. 113, no. F3, p. F03003, Jul. 2008.

[6] D. V. Shterenlicht, Hydraulics. Moscow: Lan, 2015.

[7] N. V. Zemlyanaya and S. I. Kolyagin, “Peculiarities of water distribution with variable flow systems,” Bulletin of the Engineering School of the Far Eastern Federal University, no. 1 (10), pp. 125–129, 2012.

[8] G. A. Petrov, Hydraulics of variable mass. Kharkiv: Publishing House Kharkov. University, 1964.