Article

Hydraulic jump parameters and kinetic energy dissipation downstream of hydraulic structures: a case study of the upper chirchiq water complex

Bozorova Orzigul [1], Khudoyberganov Mirzoali [2], Atakulov Dinislam *[1]

[1] Research Institute of Environmental and Nature Protection Technologies, Tashkent, 100000, Uzbekistan
[2] National University of Uzbekistan, Tashkent, 100174, Uzbekistan
o.bozorova@tiiame.uz (B.O.), mirzoaili@mail.ru (Kh.M.), dinislam.atakulov93@gmail.com (A.D.)
* Correspondence: o.bozorova@tiiame.uz; Tel.: +998973899015 (B.O.)

Abstract: This study investigates hydraulic-jump processes occurring in the downstream pools (tailraces) of hydraulic structures and hydraulic complexes, together with the problems associated with dissipating excess flow kinetic energy. Based on the Froude criterion, changes in the parameters of the supercritical flow issuing from the structure and its effects on channel-bed stability are analyzed. Mathematical relationships are presented for classifying hydraulic jumps, determining the relationship between contracted and conjugate depths, and calculating the kinetic-energy dissipation coefficient. The results can support the efficient design of energy-dissipation structures, including stilling basins and downstream aprons.

Keyword: hydraulic complex; downstream pool; hydraulic jump; kinetic energy; Froude number; contracted depth; conjugate depth; energy dissipator.

Introduction

One of the most complex tasks in the design and safe operation of hydraulic structures is the safe dissipation of the enormous energy of water released from the upstream pool into the downstream pool. Water discharging at high velocity through sluice openings and over dam surfaces possesses substantial kinetic energy. Unless this energy is dissipated over a short distance, the flow may cause severe erosion of the unprotected earthen channel in the downstream pool, which, in turn, may undermine the foundation of the structure and lead to catastrophic failures [1,5].

The transition from a supercritical flow regime to a subcritical regime in the downstream pool is accompanied by a hydraulic jump. A hydraulic jump is the principal natural mechanism for reducing excess kinetic energy in the flow; within the jump, mechanical energy is converted into thermal energy through turbulent eddies. Accurate evaluation of the parameters of this process enables the stable design of downstream structures of hydraulic complexes.

Materials and Methods

The flow state in the downstream pool of a hydraulic complex and the parameters of a hydraulic jump are primarily evaluated using the dimensionless Froude criterion. For the contracted section beneath the structure, the Froude number is determined using the following expression:

$$Fr_1^2 = \frac{U_1^2}{gh_1} = \frac{Q^2 B_1}{g\,\omega_1^3} \tag{1}$$

$$Fr_1 = Q\sqrt{\frac{B_1}{g\,\omega_1^3}} \tag{2}$$

where

Quoting: Bozorova Orzigul, Khudoyberganov Mirzoali, Atakulov Dinislam. Hydraulic jump parameters and kinetic energy dissipation downstream of hydraulic structures: a case study of the upper chirchiq water complex. **2026**, 4, 1, 3. https://doi.org/10.35938/jhee-2026-1-00003

Received: 15.04.2026
Corrected: 20.05.2026
Accepted: 25.05.2026
Published: 30.06.2026

- U_1 is the flow velocity in the contracted section (m/s);
- h_1 is the contracted depth (m);
- Q is the discharge (m^3/s);
- B_1 is the flow width (m);
- ω_1 is the wetted cross-sectional area (m^2);
- g is the acceleration due to gravity (m/s^2).

For a hydraulic jump to occur, the flow in the contracted section must be supercritical, that is, $Fr_1 > 1$. The stabilized subcritical-flow depth after the jump (h_2, the conjugate depth) is calculated using the Bélanger equation:

$$\frac{h_2}{h_1} = \frac{1}{2}\left(\sqrt{1 + 8{Fr_1}^2} - 1\right) \tag{3}$$

The amount of specific energy lost (dissipated) in the hydraulic-jump zone because of turbulent eddies and friction is determined from the energy relationship (Bernoulli equation):

$$\Delta E = E_1 - E_2 = \left(h_1 + \frac{v_1^2}{2g}\right) - \left(h_2 + \frac{v_2^2}{2g}\right) = \frac{(h_2 - h_1)^3}{4h_1h_2} \tag{4}$$

where E_1 is the total specific energy of the flow in the section before the hydraulic jump (the contracted section), and E_2 is the total specific energy of the flow in the section after the hydraulic jump (the subcritical-flow section).

The energy-dissipation coefficient, K_s, which characterizes the efficiency of kinetic-energy dissipation in the flow, is expressed as follows:

$$K_s = \frac{\Delta E}{E_1} = \frac{(h_2 - h_1)^3}{4h_1h_2\left(h_1 + \frac{v_1^2}{2g}\right)} \tag{5}$$

According to Appendix 1 to Resolution No. 143 of the Cabinet of Ministers of the Republic of Uzbekistan dated 30 March 1999, the Upper Chirchiq Water Complex was listed with a maximum discharge capacity of [22]. A recent field report states that the spillway system consists of 14 gates, each 7 m wide and 3.75 m high [23]. Due to the limited availability of detailed design and operational data, the contracted depth and the natural tailwater depth were adopted as assumed parameters for a scenario-based hydraulic assessment. Therefore, the obtained results should be interpreted as an illustrative calculation rather than a verified assessment of the current operating conditions of the structure.

Results and Discussion

Hydraulic calculations and analyses show that the nature of a hydraulic jump and the degree of kinetic-energy dissipation depend directly and strongly on the incoming Froude number. Within the study, the flow state was analyzed for different values of :

Table 1. Types of Hydraulic Jumps According to the Froude Number and Energy Dissipation Efficiency [5,12,23]

Table 1. Types of Hydraulic Jumps According to the Froude Number and Energy-Dissipation Efficiency

No.	**Froude-number range (Fr_1)**	**Type of hydraulic jump**	**Energy-dissipation coefficient (K_s)**
1	$1 < Fr_1 < 1.7$	Undular jump	$K_s < 5\%$
2	$1.7 < Fr_1 < 2.5$	Weak jump	$5\% - 18\%$
3	$2.5 < Fr_1 < 4.5$	Oscillating jump	$18\% - 45\%$
4	$4.5 < Fr_1 < 9$	Steady or stable jump	$45\% - 70\%$
5	$Fr_1 > 9$	Strong jump	$K_s \geq 70\%$

A specific practical problem arises when the natural tailwater depth in the downstream pool (h_t) is smaller than the conjugate depth (h_2), that is, $h_t < h_2$. Under these conditions, the hydraulic jump moves away from the foundation of the structure, producing a swept-out hydraulic jump [16,19].

This may create deep scour holes in the unprotected downstream reach of the hydraulic complex. To eliminate this problem, the tailwater depth h_t is increased artificially by constructing stilling basins or installing baffle blocks in the downstream pool, thereby forcing the hydraulic jump to form near the toe of the structure [17,18,20,21].

Since the width of each gate is 7 m, the total effective spillway-front width was determined as:

$$B = 14 \times 7 = 98\,\text{m} \tag{6}$$

The calculation assumes that the reported maximum discharge capacity is distributed uniformly across all 14 gate openings. Using the adopted total clear width of the gate openings, the unit discharge was calculated as follows:

$$q = \frac{Q_{\text{max}}}{B} = \frac{2000}{98} \approx 20.41\,\text{m}^2/\text{s} \tag{7}$$

For the present scenario-based hydraulic assessment, the contracted flow depth beneath the gate was assumed to be $h_1 = 1.5$ m. The mean flow velocity in the contracted section was calculated as:

$$v_1 = \frac{q}{h_1} = \frac{20.41}{1.85} = 11.03\,\text{m/s} \tag{8}$$

The following result was obtained when the Froude hydrodynamic criterion was calculated:

$$Fr_1^2 = \frac{v_1^2}{g\,h_1} = \frac{11.03^2}{9.81 \times 1.85} \approx 6.71 \tag{9}$$

$$Fr_1 = \sqrt{6.71} \approx 2.59 \tag{10}$$

The calculated Froude number, $Fr_1 = 2.59$, falls within the range $2.5 < Fr_1 < 4.5$, indicating the formation of an oscillating hydraulic jump characterized by a moderate level of energy dissipation[13,15]. Using the Bélanger equation, the second conjugate depth (h_2) was calculated as follows:

$$h_2 = \frac{h_1}{2}\left(\sqrt{1 + 8Fr_1^2} - 1\right) = \frac{1.85}{2}\left(\sqrt{1 + 8 \times 6.71} - 1\right) \approx 5.91\,\text{m} \tag{11}$$

$$v_2 = \frac{q}{h_2} = \frac{20.41}{5.91} \approx 3.45\,\text{m/s} \tag{12}$$

$$E_1 = h_1 + \frac{v_1^2}{2g} = 1.85 + \frac{11.03^2}{2 \times 9.81} \approx 8.05\,\text{m} \tag{13}$$

$$E_2 = h_2 + \frac{v_2^2}{2g} = 5.91 + \frac{(3.45)^2}{2 \times 9.81} \approx 6.52\,\text{m} \tag{14}$$

$$\Delta E = E_1 - E_2 = 8.05 - 6.52 \approx 1.53\,\text{m} \tag{15}$$

$$K_s = \frac{\Delta E}{E_1} = \frac{1.53}{8.05} \approx 0.19 = 19\% \tag{16}$$

The obtained value of $K_s = 19\%$ indicates a moderate level of kinetic-energy dissipation within the hydraulic jump.

To evaluate the downstream hydraulic condition within the adopted scenario, the natural tailwater depth was assumed to be $h_t = 4.50$ m. This value was adopted as an input parameter and does not represent a verified field measurement.

Comparison of the assumed natural tailwater depth with the calculated conjugate depth gives the following relationship:

$$h_t < h_2 \qquad (4.20\,\text{m} < 5.91\,\text{m}) \tag{17}$$

Under the adopted assumptions, the natural tailwater depth is smaller than the calculated conjugate depth. This condition indicates the potential formation of a swept-out hydraulic jump and possible downstream-bed scour.

Table 2. Results of the Scenario-Based Hydraulic Assessment for the Upper Chirchiq Water Complex

Indicator	Symbol	Value
Reported maximum discharge capacity	Q_{max}	2000 m^3/s
Total clear width of gate openings	B	98 m
Unit discharge	q	20.41 m^2/s
Assumed contracted depth	h_1	1.85 m
Velocity in the contracted section	v_1	11.03 m/s
Froude number	Fr_1	2.59
Conjugate depth (calculated)	h_2	5.91 m
Assumed natural tailwater depth	h_t	4.20 m
Velocity after the hydraulic jump	v_2	3.45 m/s
Specific energy before the jump	E_1	8.05 m
Specific energy after the jump	E_2	6.52 m
Specific energy loss	ΔE	1.53 m
Energy-dissipation coefficient	K_s	19%

Under the adopted hydraulic scenario, the calculated conjugate depth exceeds the assumed natural tailwater depth. Consequently, the hydraulic jump may not remain fully contained within the concrete-lined stilling-basin section and may shift toward the downstream natural channel. Such a condition could increase the potential for riverbed erosion and scour-hole formation. Therefore, additional energy-dissipation or tailwater-control measures may be required. However, their final design should be based on verified field measurements and official design and operational data.

Conclusions

Efficient dissipation of kinetic energy in the downstream pools of hydraulic complexes is directly related to maintaining the hydraulic jump in a stable position.

For the considered hydraulic scenario, the calculated Froude number was, corresponding to an oscillating hydraulic jump. The energy-dissipation coefficient was approximately, indicating a moderate level of energy dissipation.

At hydraulic structures where the natural tailwater depth is insufficient, additional energy dissipators, baffle blocks, or tailwater-control structures may be required to stabilize the hydraulic jump and reduce downstream-bed erosion.

Under the adopted scenario, the calculated conjugate depth exceeded the assumed natural tailwater depth. This relationship indicates the potential formation of a swept-out hydraulic jump and possible downstream-bed scour. The results represent a scenario-based assessment and should be verified using detailed field measurements and official design and operational data.

Authors' contribution

O.R.Bozorova: Conceptualization, methodology, hydraulic calculations, data analysis, visualization, and writing—original draft. M.O.Khudoyberganov: Conceptualization, methodology, supervision, and writing—review and editing. A.Y.Atakulov: Validation, formal analysis, scientific guidance, and final approval. All authors have read and agreed to the final version of the manuscript.CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

Funding source

This research received no external funding.

Ethics approval Not applicable. This study did not involve human participants, animals, or biological materials. Therefore, institutional ethical approval was not required.

Consent for publication. Not applicable. This study did not involve human participants.

Data Availability Statement The data supporting the findings of this study are contained within the article. The hydraulic calculations were performed using the input parameters described in the manuscript. Additional information is available from the corresponding author upon reasonable request.

Acknowledgments

In this section you can acknowledge any support given which is not covered by the author contribution or funding sections. This may include administrative and technical support, or donations in kind (e.g., materials used for experiments).

Conflict of interest

Declare conflicts of interest or state "The authors declare no conflicts of interest." Authors must identify and declare any personal circumstances or interest that may be perceived as inappropriately influencing the representation or interpretation of reported research results. Any role of the funders in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results must be declared in this section. If there is no role, please state "The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results".

Abbreviations

Fr	Froude Number
Fr_1	Upstream Froude Number
Ks	Energy Dissipation Coefficient

References

[1] Arifjanov, A. M., Apakxo'jayeva, Sh. S., & Xodjiyev, A. M. Hydraulics and Hydraulic Structures; Innovatsion Rivojlanish Publishing and Printing House: Tashkent, Uzbekistan, 2020.

[2] Babaali, H.; Shamsai, A.; Vosoughifar, H. Computational Modeling of the Hydraulic Jump in the Stilling Basin with Convergence Walls Using CFD Codes. *Arabian Journal for Science and Engineering* **2015**, *40*, 381–395. https://doi.org/10.1007/s13369-014-1466-z

[3] Bakiyev, M. R. Hydraulic Structures: Dams; Fan: Tashkent, Uzbekistan, 2008.

[4] Bakiyev, M. R.; Yangiyev, A. A.; Raxmatov, N. Hydraulic Structures; Ministry of Higher and Secondary Specialized Education: Tashkent, Uzbekistan, 2018.

[5] Cabinet of Ministers of the Republic of Uzbekistan. Resolution No. 143 of March 30, 1999: List of Major and Particularly Important Water-Management Facilities.

[6] Chanson, H. *The Hydraulics of Open Channel Flow: An Introduction*; Butterworth-Heinemann: Oxford, UK, 2004.

[7] Chanson, H. Current Knowledge in Hydraulic Jumps and Related Phenomena: A Survey of Experimental Results. *European Journal of Mechanics–B/Fluids* **2009**, *28*(2), 191–210. https://doi.org/10.1016/j.euromechflu.2008.06.004

[8] Chaudhry, M. H. *Open-Channel Flow*; Springer: New York, NY, USA, 2008.

[9] Champagne, T. M.; Barkdoll, B. D.; González-Castro, J. A. Experimental Study of Scour Induced by Temporally Oscillating Hydraulic Jump in a Stilling Basin. *Journal of Irrigation and Drainage Engineering* **2017**, *143*(12), 04017051. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001273

[10] Eshkou, Z.; Dehghani, A. A.; Ahmadi, A. Forced Hydraulic Jump in a Diverging Stilling Basin Using Angled Baffle Blocks. *Journal of Irrigation and Drainage Engineering* **2018**, *144*(8), 06018004. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001328

[11] Habibzadeh, A.; Loewen, M. R.; Rajaratnam, N. Performance of Baffle Blocks in Submerged Hydraulic Jumps. *Journal of Hydraulic Engineering* **2012**, *138*(10), 902–908. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000587

[12] Hager, W. H. *Energy Dissipators and Hydraulic Jumps*; Springer: Berlin, Germany, 1992.

[13] Hughes, W. C.; Flack, J. E. Hydraulic Jump Properties over a Rough Bed. *Journal of Hydraulic Engineering* **1984**, *110*(12), 1755–1771. https://doi.org/10.1061/(ASCE)0733-9429(1984)110:12(1755)

[14] Kim, Y.; Choi, G.; Park, H.; Byeon, S. Hydraulic Jump and Energy Dissipation with Sluice Gate. *Water* **2015**, *7*(9), 5115–5133. https://doi.org/10.3390/w7095115

[15] Kiselev, P. G. Handbook of Hydraulic Calculations; Energiya: Moscow, Russia, 2014.

[16] Latipov, K. Sh. Hydraulics: General Course; O'qituvchi: Tashkent, Uzbekistan, 2014.

[17] Macián-Pérez, J. F.; García-Bartual, R.; López-Jiménez, P. A.; Vallés-Morán, F. J. Numerical Modeling of Hydraulic Jumps at Negative Steps to Improve Energy Dissipation in Stilling Basins. *Applied Water Science* **2023**, *13*, 203. https://doi.org/10.1007/s13201-023-01985-4

[18] Murzyn, F.; Chanson, H. Experimental Assessment of Scale Effects Affecting Two-Phase Flow Properties in Hydraulic Jumps. *Experiments in Fluids* **2008**, *45*(3), 513–521. https://doi.org/10.1007/s00348-008-0494-4

[19] Narayana Pillai, N.; Goel, A.; Dubey, A. K. Hydraulic Jump Type Stilling Basin for Low Froude Numbers. *Journal of Hydraulic Engineering* **1989**, *115*(7), 989–994. https://doi.org/10.1061/(ASCE)0733-9429(1989)115:7(989)

[20] Peterka, A. J. *Hydraulic Design of Stilling Basins and Energy Dissipators*; Engineering Monograph No. 25; U.S. Bureau of Reclamation: Denver, CO, USA, 1978.

[21] Shulepina, N. Inspection of Hydraulic Complexes and Canals in the Middle Reaches of the Syr Darya. SREDA.UZ, 2026.

[22] Vischer, D. L.; Hager, W. H. *Energy Dissipators*; IAHR Hydraulic Structures Design Manuals, Vol. 9; A. A. Balkema: Rotterdam, The Netherlands, 1995.

[23] Wüthrich, D.; Shi, R.; Chanson, H. Hydraulic Jumps with Low Inflow Froude Numbers: Air–Water Surface Patterns and Transverse Distributions of Two-Phase Flow Properties. *Environmental Fluid Mechanics* **2022**, *22*, 789–818. https://doi.org/10.1007/s10652-022-09854-5