*ISSN 1392-1207. MECHANIKA. Vol. 30, No. 2, 2024: 144–149*

# Physical-Model-Based Assessment of Reduction of Hydraulic Forces Acting on Channel Bed through Advanced Energy Dissipator Design

**Petr ŠTEMBERK*, Martin PETŘÍK**, Jan SEDLÁK***, Milan ZUKAL****, Tomáš PICEK*******

**Czech Technical University, Thákurova 7, 166 29 Prague 6, Czech Republic, E-mail: stemberk@fsv.cvut.cz*
***Czech Technical University, Thákurova 7, 166 29 Prague 6, Czech Republic, E-mail: martin.petrik@fsv.cvut.cz*
****Czech Technical University, Thákurova 7, 166 29 Prague 6, Czech Republic, E-mail: jan.sedlak@fsv.cvut.cz*
*****Czech Technical University, Thákurova 7, 166 29 Prague 6, Czech Republic, E-mail: zukal@fsv.cvut.cz*
******Czech Technical University, Thákurova 7, 166 29 Prague 6, Czech Republic, E-mail: tomas.picek@cvut.cz*

https://doi.org/10.5755/j02.mech.33307

## 1. Introduction

The strategy of kinetic-energy dissipation of fast running water on spillways is generally determined by the geometry of the hydraulic structure and the range of discharge, when one usually decided between utilization of either the hydraulic jump or a bucket at the toe of the spillway, [1, 2]. In case of unlimited space for arranging the energy dissipation of the water flow, the design process becomes relatively easy or even entertaining. However, when a hydraulic structure is located in constrained premises and when an electric-generation unit has to be considered as well, the solution is becoming multidisciplinary as the structural performance of the hydraulic structure itself may become another serious constraint for the design of the kinetic-energy dissipation. As an example, Fig. 1 shows a simplified sketch of a small hydroelectric power plant which is an integral part of a dam whose main purpose is flood control. It should be noted in Fig. 1 that the lower part of the channel bed, from the structural point of view, serves as a roof of the underlying spaces, which may contain the power generation technology and a service gallery or the outlet channel.

Hydraulic structures, such as dams and weirs, are commonly perceived as massive concrete structures [3] which reflects the design tradition and construction technology used in the past decades [ 4, 5]. The massive here implies large amounts of concrete. However, the gradual transition to the new and more environment-friendly structural design approaches allows to design much slender structures and thus to save materials and to extend service-life of hydraulic structures, which is possible due to the rapid development in computer-assisted design methods [6] and construction technology [7]. On the other hand, the slender hydraulic structures and their components are vulnerable to the long-term erosive action of running water and the dynamic effect of the turbulent flow as the structure lacks the heavy mass. The change in the structural dynamic performance then needs to be compensated by, for example, reduction of the intensity of the turbulence and thus reduction of the hydraulic forces which load periodically the structure.

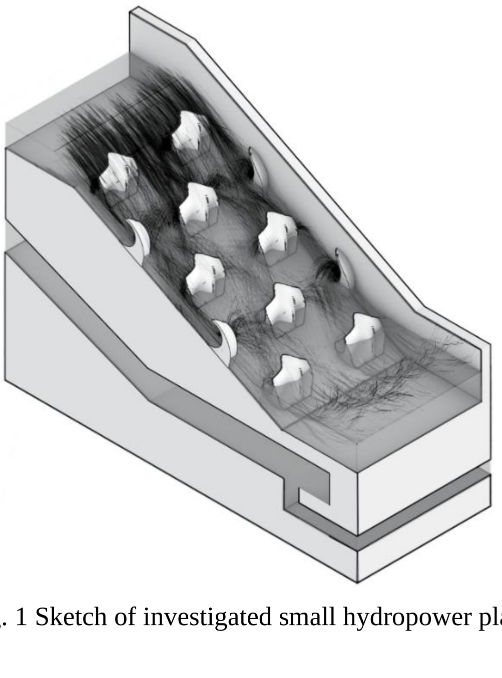
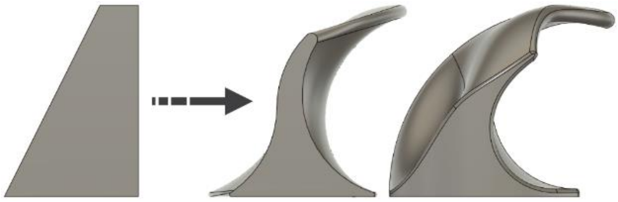


Fig. 1 Sketch of investigated small hydropower plant

The objective of this study is aimed at development of a laboratory method which can help to assess the reduction of the hydraulic forces on a structure in a cost-effective manner while still providing useful data for the subsequent full-scale design of hydraulic structures. Specifically, this study shows the approach to design of new complex shapes of energy dissipators and a physical-model-based approach to assessment of the behavior of water stream when the newly developed energy dissipators are applied. The ultimate goal is to determine the magnitude and frequency of the oscillating hydraulic forces acting on the channel bed.

## 2. Integration of new energy dissipators to hydraulic structure design

The basic design of energy dissipators made of concrete has been, and still is, constrained by the construction technology, especially, by the formwork and concrete mix design. A typical example of such widely used energy dissipators is that designed by Peterka in the 60's of past century [1] (Fig. 2, a). Despite its simple planar shape, the energy dissipating efficiency of Peterka's dissipators is satisfactory [8]. However, the tilting formwork concept, soft-skin inner surfaces of the formwork and self-compacting concrete mixture allow to produce more complex shapes (Fig. 2, b). The tilting of the formwork always provides free upper surface for air to be released from concrete while the soft-skin inner surface of the formwork allows to remove the formwork much easier, which is mainly due to the reduced effect of contraction due to shrinkage of concrete [9]. This approach allows for seeking more hydraulic-optimal shapes which are much less constrained by the production technology.

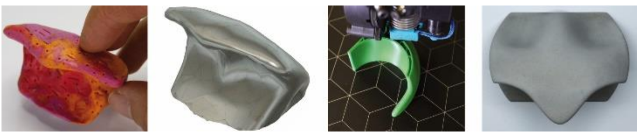


a b

Fig. 2 Transition from planar to complex shapes of energy dissipators: a – Peterka's dissipator, b – organic-shaped dissipators

In this vein, organic-shaped water energy dissipators present potential advantages over traditional square ones. These organic structures, with their naturally curved designs, appear to facilitate a range of hydraulic enhancements. Primarily, organic dissipators tend to foster rotational water motion, encouraging better aeration and effective drag. Fig. 2, b illustrates two versions of the organic dissipator, with the model on the right exhibiting a design more conducive to inducing this rotational movement of water. This vortex-like motion can entrain more air, enhancing energy dissipation and offering ecological benefits by increasing the dissolved oxygen content in water, crucial for protecting aquatic life [10, 11]. However, it is important to note that while organic dissipators are promising, their performance can vary based on environmental and flow conditions. They represent a progressive approach in hydraulic engineering, but the extent of their superiority over traditional forms is determined by specific contextual factors.

As the current and future technologies depend mainly on the quality of university graduates, it was also tried to include the students into the design process. Therefore, in order to be able to utilize the genius of the undergraduate students for hydraulic design, an appropriate design flow strategy was developed. The use of plasticine (Fig. 3, a) helped to bypass the students' lack of computer modeling skills. The plasticine models were then 3D scanned and trimmed to ensure symmetry and smooth surfaces in a CAD software (Fig. 3, b). Then, the digitized model was sliced and printed using plastic 3D printer for use in the hydraulic test channel (Fig. 3, c). Subsequently, the most promising shapes were reproduced in concrete to assess the surface quality (Fig. 3, d).



a b c d

Fig. 3 Student-friendly design flow strategy: a – plasticine model, b – 3D scanned digital model, c – plastic 3D printed model, d – concrete model

## 3. Hydraulic Performance Insights via Smoothed Particle Hydrodynamics Simulation

Following the creation of the plasticine models, an intermediate layer of verification was introduced using the Smoothed Particle Hydrodynamics (SPH) method [12]. Rather than capturing precise numeric behavior, this method was employed to validate assumptions regarding the interaction between water and the proposed dissipators. SPH, as

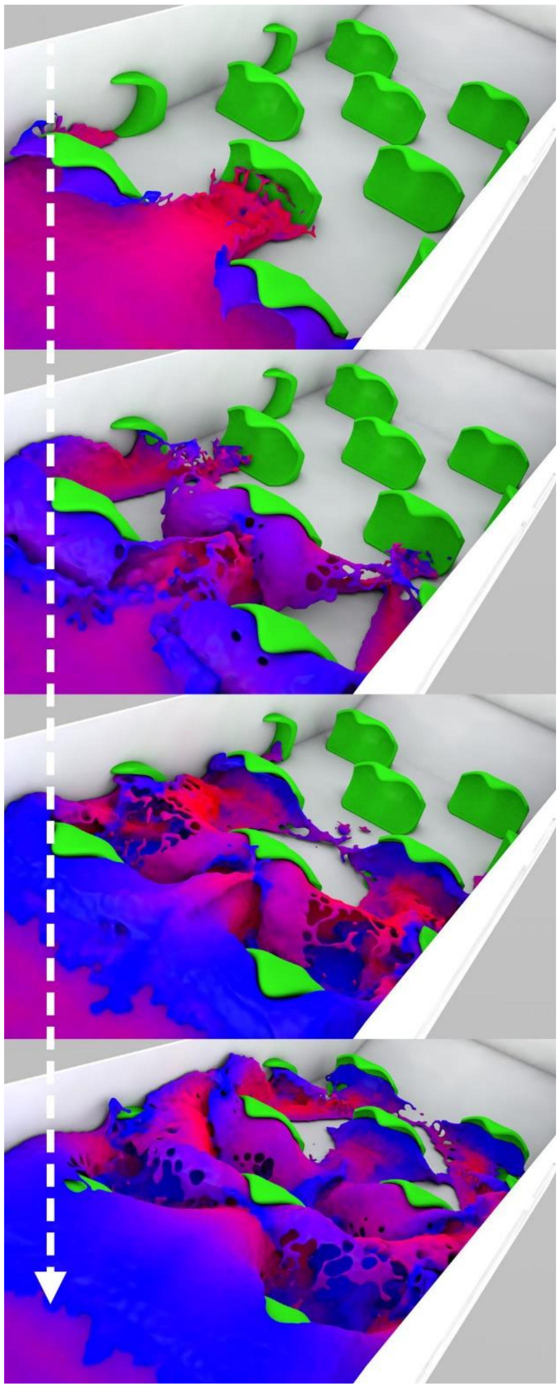


Fig. 4 Smoothed Particle Hydrodynamics (SPH) visualization illustrating water-particle interactions with the proposed dissipators

a mesh-free Lagrangian method, offers significant advantages in modeling complex fluid-structure interactions, especially when compared to grid-based techniques [13].

The absence of a mesh in SPH makes it inherently adaptable and free from constraints that often accompany grid-based methods, particularly in highly deforming regions. Moreover, while SPH can be computationally intensive due to its particle-based nature, leveraging graphics cards for calculations effectively managed these computational demands. The level of detail and adaptability SPH offers, especially in scenarios with intricate interactions, often outweighs the computational cost. The granularity of SPH ensures that localized phenomena, such as splash, jetting, or cavitation, are captured more authentically. It allows for a more intuitive and graphical representation of particle interactions, as evident from the particles striking and deflecting off the dissipators in Fig. 4. In this representation, the blue color denotes regions of low velocity, while the red color highlights areas of high velocity. Such a simulation acted as a supplementary step, offering insights into potential fine-tuning of the shape prior to digital slicing and 3D printing. This ensured a comprehensive approach, bridging the gap between hands-on model creation and the final concrete reproduction.

SPH simulations extended beyond shaping the dissipators, providing clear direction that was pivotal in determining the test channel slope. Accordingly, a 1:2 slope was established, with insights from the SPH simulations critically assessing the feasibility of alternate slopes. The 1:1 slope was found to be too steep, as the simulations revealed that the water momentum allowed it to skip over the energy dissipators, thus negating their intended function. In contrast, the 1:3 slope was considered insufficiently inclined, with SPH results showing inadequate engagement between the water flow and the dissipator complex design.

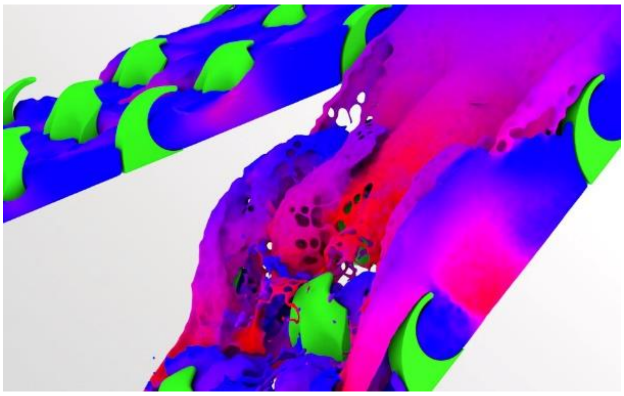


Fig. 5 Comparative SPH simulations of water behavior on 1:1 and 1:3 slopes demonstrating ineffective dissipator engagement

Fig. 5 offers a visual comparison of water behavior on 1:1 and 1:3 slopes, highlighting the ineffectiveness of both configurations. The optimal balance is achieved with the 1:2 slope, as depicted in Fig. 4, where the energy dissipators can perform their function effectively, harnessing the water momentum without overwhelming it or being underutilized.

With this approach, which includes production technology and future designers, it was ensured that the subsequent laboratory testing would be of a real value as it would be reproduceable in real structural design.

## 4. Physical model testing

Since the early developments in numerical modeling [14], continuum fluid dynamics has emerged as a powerful numerical tool for simulating hydraulic phenomena. These simulations have become integral in understanding the underlying principles of water flow and the interactions between fluid and structures. However, there are certain situations, particularly when we encounter highly turbulent flow patterns around hydraulic structures, where these computer simulations meet their limitations. The inherent complexity and unpredictable nature of turbulent flows make it challenging to capture all the intricate details accurately through numerical means alone.

Given these challenges, physical model testing has retained its significance as an indispensable tool for evaluating the hydraulic performance of structures. Unlike digital models that can suffer from oversimplification, physical models offer a tangible representation that can capture real-world nuances and interactions. Furthermore, with advancements in design and production methodologies, it has become feasible to expedite test programs. The capability to rapidly produce entire sets of energy dissipators for testing purposes, for instance, drastically reduces lead times and allows for more iterative design testing cycles.

Digitalization plays a pivotal role in both the pre-production and post-production stages. Initially, digital models are crafted, providing exact spatial data about the geometry of shapes and arrangement of the energy dissipators in the test channel. These models guide the precise creation of physical models and facilitate associated numerical analyses. Following fabrication, the physical models are digitized and compared to their original digital templates, identifying any deviations during production. This dual-layered approach fortifies the alignment between physical and numerical models, enhancing test reliability.

Fig. 6 provides a demonstrative example of this integrated approach. It showcases a small-scale test of optimized energy dissipators at a scale of 1:25 conducted in a specialized hydraulic laboratory test channel. In this depiction, the 1:25 model energy dissipators stand at a height of 48 mm, representing a seamless transition from the digital design phase to real-world testing. Such synergy between digital tools and physical testing is crucial in pushing the boundaries of hydraulic engineering and achieving designs that are both innovative and reliable.

Fig. 6 Testing of energy dissipators in test channel

The 25 cm wide test channel was used for analysis of the aerated water flow and periodic movement of the water level. It can be seen in Fig. 6 that the glass sidewalls of the test channel are equipped with a grid for easier identification of water movement which was observed using a high-speed digital camera recording the bubble movement against backlight. Such a configuration not only highlighted the bubble paths with pronounced contrast but also allowed for a deeper understanding of their behavior and interactions within the flow.

## 5. Analysis of static force on channel bed

As with the real-scale hydraulic structures, the small-scale physical model is also fully flooded which prohibits simple measurements of structural vibration. Then, it is necessary to determine the acting loading forces and assess the vibration behavior numerically. In case of hydraulic forces which act on the channel bed, the decisive factors are the depth of water and its velocity (flow rate) and density (depending on aeration). The simplified geometry of the physical model of the test channel is shown in Fig. 7, which represents an investigated small hydropower plant, where the average depth $h_1$ is 0.042 m, the average depth $h_2$ is 0.113 m, the flow rate $Q_m$ is 6.29 kg/s (at $\rho$ = 999 kg/m$^3$) and the length of the channel bed $L$ is 0.3 m.

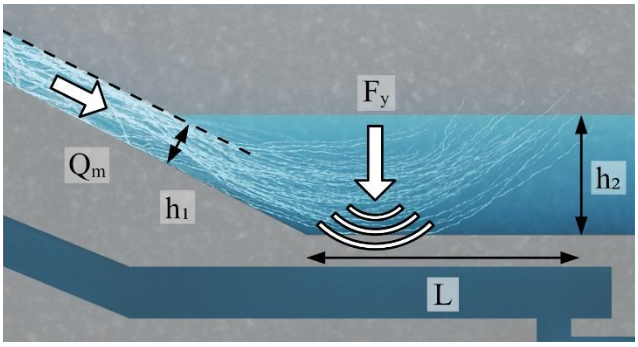



Fig. 7 Investigated small hydropower plant

As a simplified alternative to the full-scale assessment of the water pressure on the channel bed can be assess, which would be done using the continuum fluid dynamics, it was tried to assess the magnitude of the hydraulic force acting on the channel bed using the impulse-momentum approach [15], when the Newton's second law of motion applied for the mass and velocity of flowing water yields the force which acts on the channel bed. In this way, the static average component, the minimum and the maximum could be obtained. The frequency of the oscillation was obtained using the optical flow, which is a valuable information for both the analysis of the dynamic effects of water on the channel bed and the potential fatigue behavior of the bed structure.

From the hydraulic measurements, the following values were obtained. For the average depth $h_1$, the minimum and maximum values were 0.04 m and 0.044 m, respectively. For the average depth $h_2$, the minimum and maximum values were 0.108 m and 0.118 m, respectively. The density of the water/air mixture at the position $h_1$ was the average 878 kg/m$^3$, the minimum was 838 kg/m$^3$ and the maximum was 922 kg/m$^3$. At the position $h_2$, the average density 985 kg/m$^3$, the minimum was 943 kg/m$^3$ and the maximum was 999 kg/m$^3$.

From the momentum theorem, it is possible to express the force $\vec{F}$ which the water flow exerts on the channel bed from the following formulas

$$\vec{F} = \vec{F}_{p1} + \vec{F}_{p2} + \vec{G} + \rho_1 \cdot Q_1 \cdot \vec{v}_1 - \rho_2 \cdot Q_2 \cdot \vec{v}_2, \tag{1}$$

$$\vec{F}_{p1} = \rho_1 \cdot g \cdot b \cdot \frac{1}{2} \cdot h_1^2 \cdot cos\,\delta, \tag{2}$$

$$\vec{F}_{p2} = \rho_2 \cdot g \cdot b \cdot \frac{1}{2} \cdot h_2^2, \tag{3}$$

where $\vec{F}_{p1}$ is the pressure force at the inlet acting in the direction of the velocity $\vec{v}_1$ and assuming the hydrostatic pressure distribution, and $\vec{F}_{p2}$ is the pressure force at the inlet acting in the direction of the velocity $\vec{v}_2$ and assuming the hydrostatic pressure distribution. $Q_1$, with an average value of 0.007161 m$^3$/s, represents the spillway flow rate, while $Q_2$, having an average value of 0.0063845 m$^3$/s, denotes the bed flow rate, and $b$ indicates the width of the test channel of 0.25 m. $\vec{G}$ is the gravity of water (water/air mixture) $\rho_1$ and $\rho_2$ are the respective densities of water/air mixture. Since the chute is sloped at the gradient of 1:2 (vertical to horizontal), the angle $\delta$ at the foot of the sloping chute is 27 degrees. The vertical component, $\vec{F}_{vert}$, of the resulting force acting on the channel bed is then obtained in the following form

$$\vec{F}_{vert} = \vec{F}_{p1} \cdot sin\,\delta + \rho_1 \cdot Q_1 \cdot \vec{v}_1 \cdot sin\,\delta + \vec{G}, \tag{4}$$

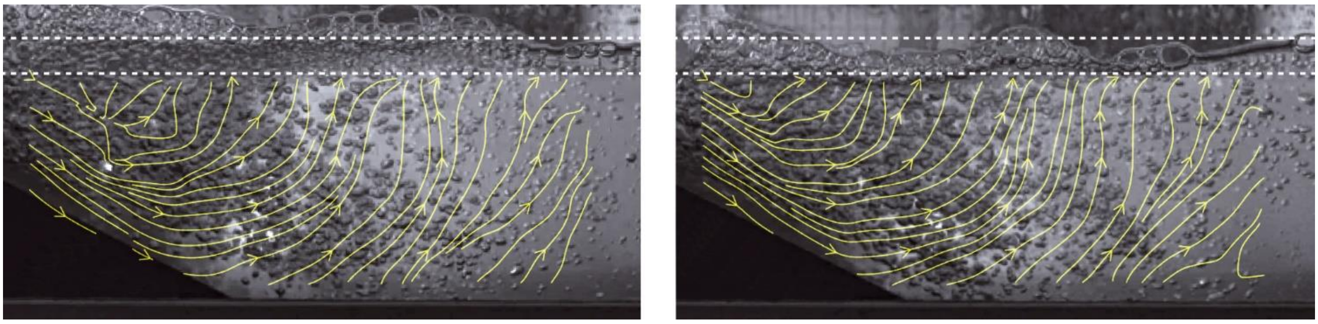
when the average value is 81.99 N, the minimum is 81.91 N and the maximum is 82.02 N. Since the scatter of the acting force is around 0.1 %, in this case, the dynamic effect of the water flow can be neglected in subsequent the structural design. Despite this fact, for the general applicability of the proposed approach, the dynamic change of the acting force was also investigated.

## 6. Analysis of turbulences using optical flow

Since the dynamic behavior of the hydraulic forces may affect the stability and durability of the hydraulic structures, another goal of this research was to develop a method for mapping this phenomenon, which would provide a quantitative measure for comparison of efficiency of different types of the designed energy dissipators.

The frequency of the periodic changes in water depth and the density of the water/air mixture within the turbulent water flow was investigated using Optical Flow, specifically employing the Lucas-Kanade method [16]. This method was chosen due to its ability to effectively track local motion patterns using pixel intensity variations, making it suitable for applications where intricate flow details, such as bubble movement, are to be observed without the need for seeding particles [17]. In the experimental setup, a high-speed camera was deployed to record videos, capturing the natural inconsistencies, like bubbles, within the flow, which served as indicators of water movement. Backlighting was crucial in amplifying contrast, while maintaining a fixed focus was essential for recognizing the motion across different longitudinal sections. Subsequent to recording, the data underwent a noise reduction process to yield a clearer depiction of the flow patterns, as exemplified in Fig. 8.

In Fig. 8, images from two distinct temporal points are displayed, illustrating the highest and lowest water levels. Remarkably, despite the change in water levels, the trajectories of air bubbles remain consistent in both scenarios. This uniformity in the paths, especially their direction and magnitude, offer valuable insights into the force vectors consistent within the flow, regardless of the water level. The constancy in bubble trajectories despite varying water levels underscores the stable flow behavior, highlighting the potential of the dissipators in maintaining controlled energy levels even under differing hydraulic conditions. These observations are crucial as they not only demonstrate the operational efficacy of the energy dissipators but also help in comprehending the potential forces that the structures are subjected to. The nuanced understanding gained from these



a b

Fig. 8 Example of images showing alteration in water level and principal trajectory of air bubbles: a – highest, b – lowest

trajectory analyses is crucial in enhancing the precision of hydraulic simulations and, consequently, in the informed engineering of more robust and efficient hydraulic structures.

A standard tool for analyzing the frequency nature of data is the Fourier analysis, which was performed in Matlab. In this study, it was not necessary to study in detail the flow characteristics of the whole sample, it is sufficient to focus on the periodic changes of the vertical coordinates ($y$) at the water level and at the bottom, which could potentially stress the underlying structure. A set of 950 frames from an eight-second video was examined for each energy dissipator. Let us denote the sequence of the average $y$ coordinates by $y = (y_1, y_2, y_3, ..., y_n)$. The Fourier transform $Y = (Y_1, Y_2, Y_3, ..., Y_n)$ for a vector $y$ is defined as follows

$$Y_{k+1} = \sum_{j=0}^{n-1} e^{\frac{2ijk\pi}{n}} y_{j+1}. \quad (5)$$

A more detailed description of FFT application can be found, for example, in [18].

Fig. 9 shows the resulting frequency domain of the average $y$-coordinate values of a group of vectors at the water level related to the water level changes. The graph suggests that there are dominant frequencies between 0.55-0.65 Hz. This also means that the turbulences do not occur at a specific frequency, rather there are several turbulent patterns at a specific frequency band. Currently, the verification could be done only by comparison the observation of the periodicity of the water level movement, which oscillated between the periods of 1.5 and 2 s, which corresponds with the frequencies of about 0.5 and 0.67 Hz. A more rigorous method of verification needs to be yet developed.

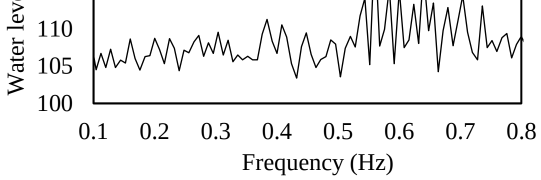



Fig. 9 Frequency domain of turbulences near water level

## 7. Conclusions

The described research work resulted in the following findings. Firstly, the low-cost approach with absence of complicated laboratory equipment and complex software packages allows the undergraduate students to join the research activities which provide useful results. Here, plasticine, a mobile, free photogrammetry software or a simple 3D scanner, and a plastic 3D printer are sufficient for developing new shapes of energy dissipators. Secondly, the preliminary assessment of the hydraulic forces, which act on the hydraulic structures, can be performed using the basic physical laws, such as Newton's second law of motion, instead of complex continuum fluid dynamics modeling, which is more fitting in the later stages of analyses at real scales for only few candidate solutions. Thirdly, optical flow proves to be a valid tool for laboratory physical model testing when a sufficiently fast camera, with a frame rate above 120 fps, fixed focus capability, and backlighting, is the only necessary equipment. The image processing then can provide information about water movement and possibly about the degree of aeration based on water transparency.

## Acknowledgements

This work was financially supported by the Czech Science Foundation, project 20-25995S, and SGS23/038/OHK1/1T/11 which are gratefully acknowledged.

## References

1. **Peterka A. J.** 1964. Hydraulic design of stilling basins and energy dissipators. U.S. Dept. of the Interior, Bureau of Reclamation; 1964. Engineering monographs, no. 25.
2. **Rhone, T. J.** 1977. Baffled apron as spillway energy dissipator, Journal of the Hydraulics Division 103(12): 1391-1401.
3. **Novak, P.; Moffat, A.I.B.; Nalluri, C.; Narayanan, R.** 2007. Hydraulic Structures. London and New York: Taylor & Francis. 700p. https://doi.org/10.1201/9781315274898.
4. **Chanson, H.** 2002. The hydraulics of stepped chutes and spillways. Grafisch produktiebedrijf Gorter. Steenwijk. The Netherlands.
5. **Chanson, H.** (Ed.). 2015. Energy dissipation in hydraulic structures. Boca Ration: Taylor&Francis Group. https://doi.org/10.1201/b18441.
6. **Li, J.Z**. 2015. CAD, 3D Modeling, Engineering Analysis, and Prototype Experimentation. Berlin: Springer. 255p. https://doi.org/10.1007/978-3-319-05921-1.

7. **Lloret, E.; Shahab, A. R.; Linus, M.; Flatt, R. J.; Gramazio, F.; Kohler, M.; Langenberg, S.** 2015. Complex concrete structures: Merging existing casting techniques with digital fabrication, Computer-Aided Design 60: 40-49. https://doi.org/10.1016/j.cad.2014.02.011.
8. **Bestawy, A**. 2013. New shapes of baffle piers used in stilling basins as energy dissipators, Asian Transactions on Engineering 3(1): 1-7.
9. **Petřík, M.; Štemberk, P.; Zukal, M**. 2023. Exploration of Advanced Fabrication Techniques for Organic Shaped Energy Dissipators in Spillways, Journal of Advanced Concrete Technology 21(4): 262-270. http://dx.doi.org/10.3151/jact.21.262.
10. **Salmasi, F.; Abraham, J.; Salmasi, A.** 2021. Effect of stepped spillways on increasing dissolved oxygen in water, an experimental study, Journal of Environmental Management 299, 113600. https://doi.org/10.1016/j.jenvman.2021.113600.
11. **Jaiswal, A.; Goel, A.** 2019. Aeration through weirs – a critical review. Sustainable Engineering: Proceedings of EGRWSE 2018: 187-200. http://dx.doi.org/10.1007/978-981-13-6717-5_19.
12. **Gomez-Gesteira, M.; Rogers, B. D.; Dalrymple, R. A.; Crespo, A. J.** 2010. State-of-the-art of classical SPH for free-surface flows, Journal of Hydraulic Research 48(sup1): 6-27. http://dx.doi.org/10.1080/00221686.2010.9641242.
13. **Violeau, D.; Rogers, B. D.** 2016. Smoothed particle hydrodynamics (SPH) for free-surface flows: past, present and future, Journal of Hydraulic Research 54(1): 1-26. http://dx.doi.org/10.1080/00221686.2015.1119209
14. **Olsen, N. R.; Kjellesvig, H. M.** 1998. Three-dimensional numerical flow modelling for estimation of spillway capacity, Journal of Hydraulic Research 36(5): 775-784. https://doi.org/10.1080/00221689809498602.
15. **Marriott, M.** 2016. Nalluri And Featherstone's Civil Engineering Hydraulics: Essential Theory with Worked Examples, 6th Edition. Wiley-Blackwell. 480p.
16. **Lucas, B. D.; Kanade, T.** 1981. An iterative image registration technique with an application to stereo vision. In IJCAI'81: 7th international joint conference on Artificial intelligence 2: 674-679.
17. **Zhang, G.; Chanson, H.** 2018. Application of local optical flow methods to high-velocity free-surface flows: Validation and application to stepped chutes, Experimental Thermal and Fluid Science 90: 186-199. http://dx.doi.org/10.1016/j.expthermflusci.2017.09.010.
18. **Shin, K.; Hammond, J.** 2008. Fundamentals of Signal Processing for Sound and Vibration Engineers. John Wiley & Sons Inc. 416p.


P. Štemberk, M. Petřík, J. Sedlák, M. Zukal, T. Picek

PHYSICAL-MODEL-BASED ASSESSMENT OF REDUCTION OF HYDRAULIC FORCES ACTING ON CHANNLE BED THROUGH ADVANCED ENERGY DISSIPATOR DESIGN


S u m m a r y

The hydraulic engineering designers focus on shaping up the flow regime so that the greatest energy dissipation is ensured. On the other hand, the structural designers focus on load bearing capacity and durability of the structural components which may contradict the focus of the hydraulic experts. Such a case may occur when the spillway chute floor slab must be thin due to the limited spaces. Then, the dynamic load acting on the chute floor slab may compromise its long-term operation. The dynamic forces are created by the violent turbulences which may even coincide with the natural frequency of the reinforced concrete floor slab. Therefore, the objective of this paper is a complex approach to small-scale physical model testing which makes use of the latest rapid-prototyping techniques and the optical flow, and which in the end allows to estimate the magnitude of the dynamic hydraulic forces acting on the channel bed. The newly developed organic-shape energy dissipators play a key role in reducing the kinetic energy of water through its enhances aeration. The proposed method on a small scale can assist favorably the design process of real-scale hydraulic reinforced concrete structures.



**Keywords:** rapid prototyping, hydraulic structures, energy dissipation, physical-model testing, optical flow.

Received January 29, 2023
Accepted April 15, 2023