WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2020.135234
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVI ISSUE 4 2020

THE IMPACT OF ENERGY DISSIPATION DEVICES ON THE SIZE OF LOCAL SCOUR BEDS ON THE SLUICE GATE MODEL

J. URBAŃSKI[1], M. KIRAGA[2], S. BAJKOWSKI[3]

The article presents the results of experimental research aimed at recognizing the impact of the design of energy dissipation devices on the formation of bed local scouring below the sluice gate. The experiments were carried out on a model of a sluice gate built in a rectangular flume with a width of 0.58 m, with the outflow of the stream from under the slider to a horizontal bed 0.80 m long. Behind the dam gate valve three different constructions of energy dissipation devices were used: flat, horizontal slab, slab equipped with baffle blocks arranged in two rows and rip-rap. The experiments assumed forming a scour hole in 480 minutes downstream the sluice, where the bed was filled with sorted sand. The depths of the scour were measured in the longitudinal profile after 30, 60, 90, 120, 180, 240, 300, 360, 420 and 480 minutes. The deepest scour holes of the bed, both in terms of depth and length, occurred on the structure model with energy dissipation devices made as a flat, horizontal plate. At the same time, in this case, the hole was developing the most rapidly, and its shape and size posed the greatest threat to the stability of the structure. The use of baffle blocks arranged in two rows or a rip-rap behind the structure slide noticeably reduced the size of the scour and delayed the erosion of the bottom in time, as compared to the course of this process on a model with a flat, horizontal slab.

Keywords: local scouring, hydraulic model studies, energy dissipation devices, sluice gate

---

[1] DSc., PhD., Eng., Warsaw University of Life Sciences WULS-SGGW, Institute of Civil Engineering, Ul. Nowoursynowska 159, 02-787 Warsaw, Poland, e-mail: janusz_urbanski@sggw.edu.pl
[2] DSc., PhD., Eng., Warsaw University of Life Sciences WULS-SGGW, Institute of Civil Engineering, Ul. Nowoursynowska 159, 02-787 Warsaw, Poland, e-mail: marta_kiraga@sggw.edu.pl
[3] DSc., PhD., Eng., Warsaw University of Life Sciences WULS-SGGW, Institute of Civil Engineering, Ul. Nowoursynowska 159, 02-787 Warsaw, Poland, e-mail: slawomir_bajkowski@sggw.edu.pl

1. INTRODUCTION

The flume in the lower hydraulic structure stand is exposed to the influence of water discharges with very high variability, from extremely small to maximum: base or control discharge. As a result, its bottom and slopes are scoured by flowing waters, and the bed is washed out by filtering waters through the ground. These phenomena and the water coverage of the adjacent area also make it difficult to conduct foundation works, about which Pisarczyk [1] writes. The formation of local scour hole is one of the most difficult research issues in hydrotechnics, and its recognition has great practical importance. Excessive development of the local erosion of the flume bed can lead to channel fortifications destruction in the lower site of the structure, exposing its foundation, and even causing the loss of stability [2; 3]. Due to these risks at the design stage it is very important to prepare a forecast of the size of the scour hole. In practice, however, this proves difficult because the process of increased channel erosion, due to its high degree of complexity, is still not sufficiently recognized.

The formation of local scour is the subject of many publications presenting a wide range of research conducted for several decades, most often in laboratory conditions. The research primarily concerned recognition of the influence of various factors on the magnitude of the emerging scour, including hydraulic parameters of the stream, soil grain size and flow duration [4-11]. Based on the literature review and the results of this research, extensive studies were performed on the processes of local erosion of river beds [9; 12; 13]. Difficulties in recognizing the aforementioned process and its mechanism result, among other things, in the complexity of phenomena occurring in a hydraulic jump at the fall of a structure and the simultaneous separation and transfer of soil particles by a turbulent stream [11; 14-23]. Apart from physical modelling of the erosion, attempts were also made to adapt computer simulation methods using a two-phase flow model to recognize these processes [20-27]. Current research direction of scouring downstream the hydraulic structures is to conduct simulations using three-dimensional numerical models, considering the turbulent nature of water discharge [28; 29]. Due to the complexity of the phenomenon and the multitude of factors influencing its course, these attempts did not always give satisfactory results. Still, one of the most accurate methods of forecasting the size of a scour hole is laboratory tests on physical models reflecting real structural solutions of the structure. In this way, the impact of the applied technical solutions and their modifications on the scour hole dimensions can be assessed.

One of the methods of reducing the amount of scouring below the structure is the use of appropriate energy dissipation devices. Their task, in the case of structures located on lowland rivers, is primarily to create the right conditions for a hydraulic jump. For this purpose, a solid slab in the lower stage of the structure or a local lowering of the bed from the outflow side, named a dissipation basin, is most commonly used, or the obstacles causing a local piling up at the outflow in the form of a threshold or concrete blocks (baffle blocks). Model studies on the influence of the construction of energy dissipation devices on the magnitude of local scouring below hydraulic structures have been conducted for many years [7; 12; 18; 30-36], among others, because of their practical application in construction design. According to the applicable regulations, defined in the Regulation ... [37], "for hydrotechnical structures of class I and II, the capacity and shape of hydrotechnical discharge structures and devices for dissipation of water energy is tested by model tests". Appropriately designed and constructed energy dissipation devices ensure jet velocity reduction and thereby the size of the scour hole is reduced and local scour evolution latency in time. This was demonstrated, among others, by Urbański's research [30- 32], carried out on a structure model with reinforcement in the lower stage, with various reinforcement length and the roughness of its surface.

In the paper, a comparative analysis of laboratory test results was conducted, describing local scouring process on a model of a sluice gate, on the lower stand of which variously designed energy dissipation devices were used, typical for structures located on small lowland rivers. A great threat to the structures' safety is posed by the scouring downstream the objects with a flat horizontal slab. That is why the model of sluice gate equipped with flat slab plate was adopted in the research presented in the article. The influence of the lower stand construction on the parameters characterizing the scour hole in terms of building safety was analyzed. The group of scour characteristics such as the maximum depth of the scour, the distance of occurrence of the greatest scour depth from the end of the outflow and the shape of the hole was described. These parameters are most often taken into account in the assessment of the efficiency of energy dissipation devices [12]. The criteria adopted to assess the safety of water structures were published in the works of Bajkowski et al. [38] and Bajkowski [2].

2. CRITERIA FOR ASSESSING THE SAFETY OF WATER STRUCTURES

The safety of earthen hydro-engineering structures, often built due to the simplicity of construction, low costs, long life span, and wide possibilities of adaptation to topographical and geological conditions is usually considered without or with the stabilization of erosion processes [39]. This assessment often overlooks other factors shaping the security of facility usability, beyond the environmental impacts, which currently include terrorist acts, which are increasing in various forms. Duchaczek & Skorupka [40], pointing out the role of critical communication infrastructure responsible for the movement of goods and materials, includes bridges, underground passages and culverts as the main ancillary equipment for direct control of roads and transport [40]. The authors took into account five criteria for assessing the likelihood of destruction of bridge facilities: K1 - distance from the city centre, K2 - traffic intensity on the bridge, K3 - destruction of spans or intermediate supports, K4 - bridge material, K5 - bridge construction. Historically speaking bridges were usually one of the first victims of armed conflicts, but also the first to be rebuilt after the post-war destruction [41]. The safety of bridge structures and dammed hydrotechnical structures depends to a large extent on the intensity of natural erosion processes which increase the risk of the facility being taken out of service or its failure. A construction disaster may be caused by mistakes made at each stage of the investment process, i.e. planning an investment, construction or use of a building object [42].

According to Dąbkowski and others [12] the inclination of the straight line passing through the end of the outflow and the bottom of the scour hole at the place of its maximum depth could be used as a criterion in the assessment of the safety of water structures (line 3 on Figure 1). The inclination of this straight line may be expressed by a ratio of 1:m_β, in which m_β is equal to $ctg\beta = L_{max}/h_{max}$. The values of this coefficient are related to the position of the scour hole relating to the structure and its shape and the slope of bottom within the scour hole area. According to Dąbkowski et al. [12], for existing structures when $ctg\beta \le 2$ it is necessary to proceed with safety works as soon as possible; when $2 < ctg\beta \le 5$ it is essential to increase the frequency of measurements and observations of the erosion and start preparations for repair, and when $ctg\beta \approx 8$ the condition of the structure is considered sufficiently safe.

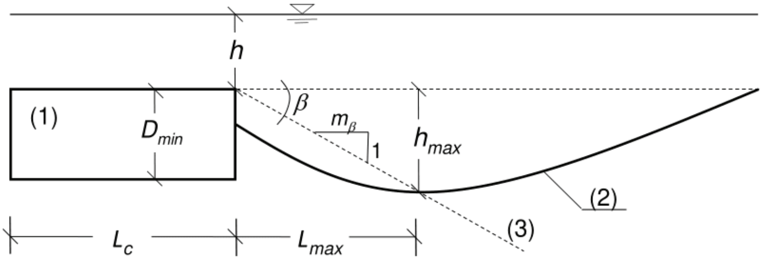


Fig. 1. Safety line β angle determination schematics, where (1) – structure foundation, (2) local scour profile, (3) – safety line

Fig. 1 also presents a scheme of the structure foundation (1) with depth D_{min} and length L_c. These are crucial parameters for the foundation design, which are included in the equations describing the structures' safety factors. Particularly in the case of hydrotechnical structures, which stand at the interface between the ground and water environment, it is important to properly design the foundation due to the risk of lift and displacement of the slab. According to Bajkowski and others [38] the limiting values of the safety line slope coefficient, lower (ctgβ_d) and upper (ctgβ_g), can be described by equations (2.1) and (2.2) obtained basing on the criterion of ground displacement from the foundation of the structure:

$$ctg\beta_d = \frac{1}{2fn} tg^2\left(45^\circ + \frac{\varphi}{2}\right) + ctg\alpha\left(1 - \frac{1}{2n}\right) \quad (2.1)$$

$$ctg\beta_g = \frac{p}{n}\frac{cos\xi_p}{cos\xi_L} exp\left(\frac{\pi}{2} tg\varphi\right) + \frac{1}{n}\frac{1}{tg\xi_p} ctg\alpha \quad (2.2)$$

where:

$p = \frac{L_C}{D_{min}} = \frac{n}{s}$ – the length factor of the base of the foundation

$n = \frac{h_{max}}{D_{min}}$ – foundation depth factor,

$s = \frac{h_{max}}{L_C}$ – local scour depth factor,

$\xi_L = \left(\frac{\pi}{4} + \frac{\varphi}{2}\right), \xi_p = \left(\frac{\pi}{4} - \frac{\varphi}{2}\right)$ – the inclination angles of the left and right sliding surfaces,

α – inclination angle of the local scour slope downstream the slab,

$f = \text{tg}\ \varphi$ – friction coefficient [-],

φ – angle of internal friction of the ground,

γ – volumetric weight of the ground [N·m^{-3}],

D_{min} – minimum depth of foundation [m],

L_C – length of foundation slab [m].

In the paper, the limit values of the critical inclination coefficient of the line were calculated, assuming after Bajkowski et al. [38] and Bajkowski [2]: α=20°, p=8, k=1, n in the range from 1.0 to 12. The angle of internal friction of the ground φ was assumed to equal 33° due to the application of thick sand in the medium compacted state on the model. Against the background of the limit values, the results of the measurements of the scouring formed on the model with different structures of the lower stand were presented and the degree of stability hazard of the modelled structure was assessed.

3. MATERIALS AND METHODS

The scheme of the test stand and variants of the model used in the research are presented in Fig. 2. The test stand (Fig. 2a) was a horizontal, rectangular flume with a width of 0.58 m, depth of 0.40 m and length of 8.0 m. The water was supplied with a steady flow rate, which was controlled by the use of an electromagnetic flow meter located on the inlet pipe.

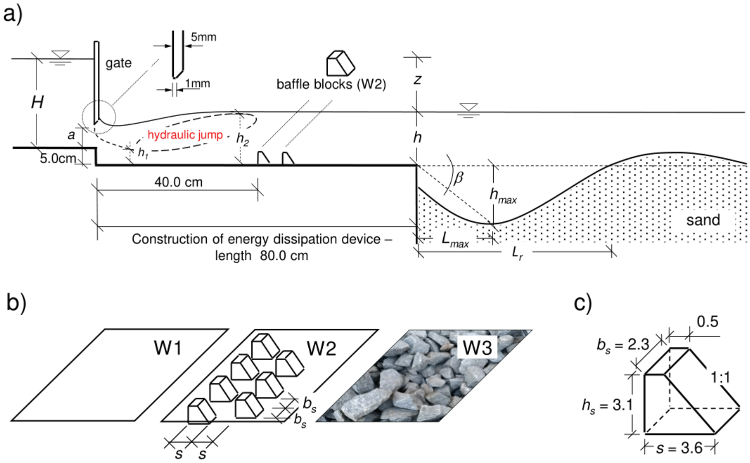


Fig. 2. Schema of the research models: a – the structure model and analysed parameters of local scour, b – variant constructions of energy dissipation devices, c – dimensions of baffle blocks [cm]

The main element of the model was a flat gate valve that piled up the water in the channel, installed in its central part and lifted to a level above the threshold of 0.05 m (Fig. 2a). The stream of water flowed out from under the gate valve to a horizontal, reinforced bottom 0.80 m long, where a hydraulic jump was formed. In the further section, the bottom of the flume was filled with sand, where the stream of water flowing out formed a scour hole. In the lower stand a constant water level was maintained.

Three different design variants of the energy dissipation devices were used in the section behind the damming gate. These were successively:

W1 - flat, horizontal slab, made of plastic,

W2 - slab with baffle blocks (25 pieces in total) arranged in two rows,

W3 - rip-rap with relative roughness $\varepsilon=(k_s/h)$ in the range of 0.061÷0.078, made of broken stone with the grain size curve shown in Fig.3.

The experiments for each tested variant of the construction of energy dissipation devices were carried out under established hydraulic conditions according to the parameters given in Table 1.

Table 1. Hydraulic flow parameters in model experiments

q	H	h	a	h_1	h_2	σ_z
m^2s^{-1}	m	m	m	m	m	-
0.0283	0.305	0.118	0.011	0.0109	0.117	1.01
0.0371	0.308	0.136	0.017	0.0143	0.133	1.02
0.0466	0.310	0.150	0.024	0.0181	0.147	1.02

The first coupled depth h_1 was calculated using Bernoulli's equation (3.1) related to the cross-section of its occurrence in the following form:

$$E_1 = h_1 + \frac{\alpha q^2}{2gh_1^2} \ [\mathrm{m}] \quad (3.1)$$

where:

α – Coriolis coefficient (1.1 value assumed),

g – gravity acceleration (9.81 ms^{-1} value assumed).

The calculation assumes that the amount of energy in the cross section of the first coupled depth E_1 is equal to the total energy E of the stream flowing into the gate valve, calculated in relation to the bottom in the lower stand from formula (3.2):

$$E = H + \frac{\alpha v^2}{2g} + 0.05 \ [\mathrm{m}] \quad (3.2)$$

in which $v=q/H$ is the average speed of the input stream [ms^{-1}].

The second coupled depth h_2 is calculated from the equation (3.3):

$$h_2 = \frac{h_1}{2}\left(\sqrt{1 + 8\frac{q^2}{gh_1^3}} - 1\right) \ [\mathrm{m}] \quad (3.3)$$

The hydraulic jump submergence coefficient σ_z is calculated from the ratio h/h_2, where h is the water depth in the lower stand.

The experiments included measurements of the local scour shape formed in the lower structure stand, where the bottom of the flume was filled with sorted sand with the grain size curve shown in Figure 3. The discharge duration was 480 min. The depths of the scour holes were measured in the longitudinal profile in the axial plane of the flume after 30, 60, 90, 120, 180, 240, 300, 360, 420 and 480 minutes from the beginning of the experiment. The analyzed scour dimensions (L_{max}, h_{max}, L_r) are shown in Fig. 2.

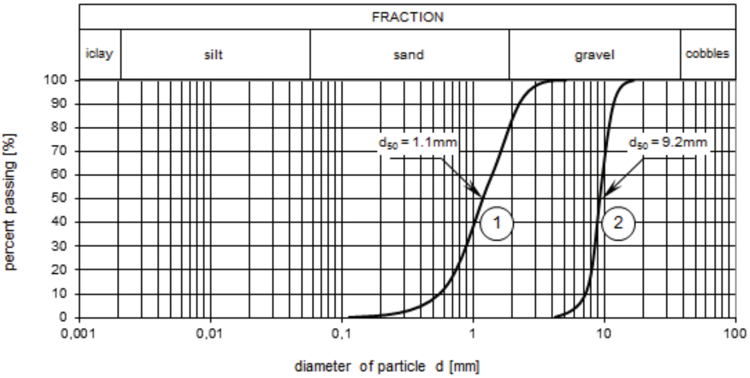
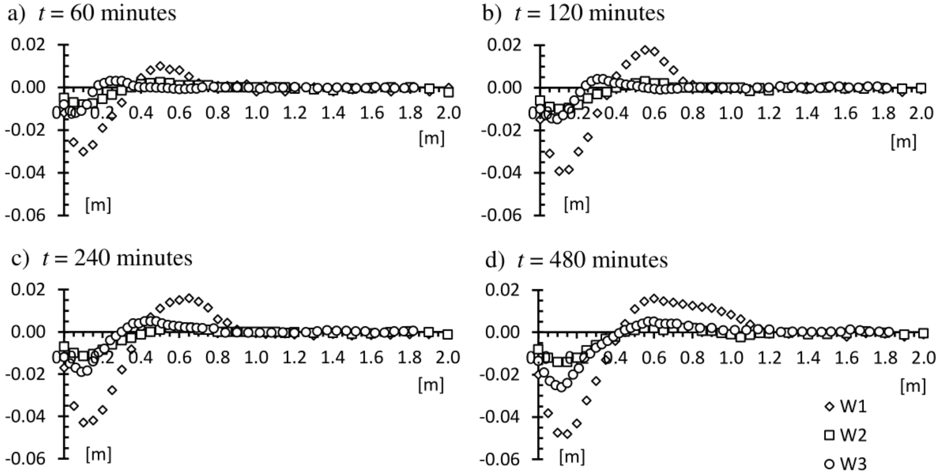


Fig. 3. Granulation curves: 1 – bed sediment, 2 – rip-rap

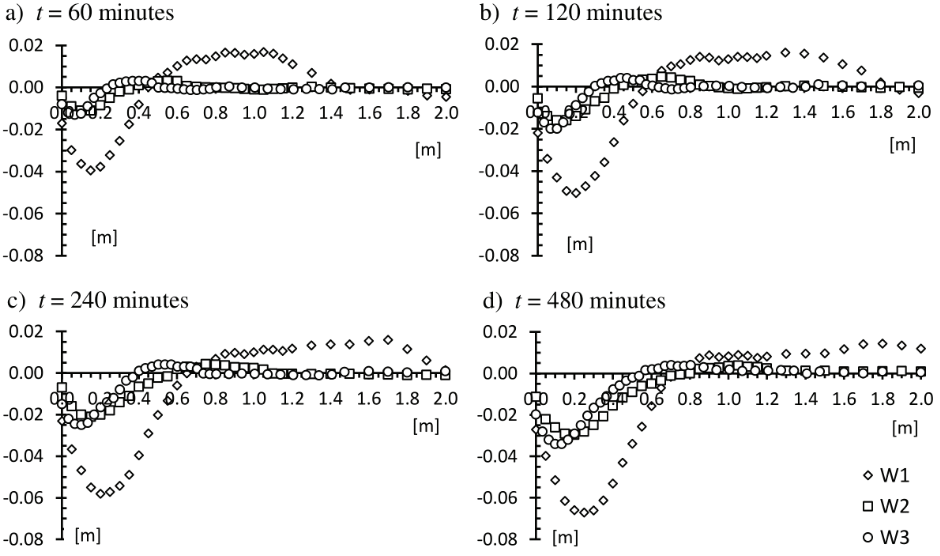
4. RESULTS AND DISCUSSION

Figures 4, 5 and 6 present longitudinal profiles of the scoured bottom, shaped at 60, 120, 240 and 480 minutes flow time on the model using different structures of energy dissipation devices (W1, W2, W3). The sizes of the scour hole, both its depth and length increased during the flow and did not achieve final stabilization however there were only minor changes of scour depth after 480 minutes. Behind the local scour, an outwash of the eroded material was formed, which moved along the bottom over time, and its maximum height was at an increasing distance from the end of the outflow. The simultaneous location of the points on the scoured bed diagrams shaped by a stream of the same hydraulic parameters clearly shows the impact of the type of energy dissipation devices used on the size of the scour hole. The largest size of a local scour, i.e. both its depth and length, was obtained by using a flat, horizontal slab on the outflow. In the other two cases, i.e. using baffle blocks arranged in two rows or a rip-rap, the dimensions of the scour were much smaller. The application of the structure with an increased roughness on the slab surface has an impact on scour size diminishing, which was also been proved by Urbański [18] and Hossam et al. [34].



a) t = 60 minutes b) t = 120 minutes c) t = 240 minutes d) t = 480 minutes

Fig. 4. Profiles of scour after t time duration of flow rate $q = 0.0283\ \text{m}^2\text{s}^{-1}$



a) t = 60 minutes b) t = 120 minutes c) t = 240 minutes d) t = 480 minutes

Fig. 5. Profiles of scour after t time duration of flow rate $q = 0.0371\ \text{m}^2\text{s}^{-1}$

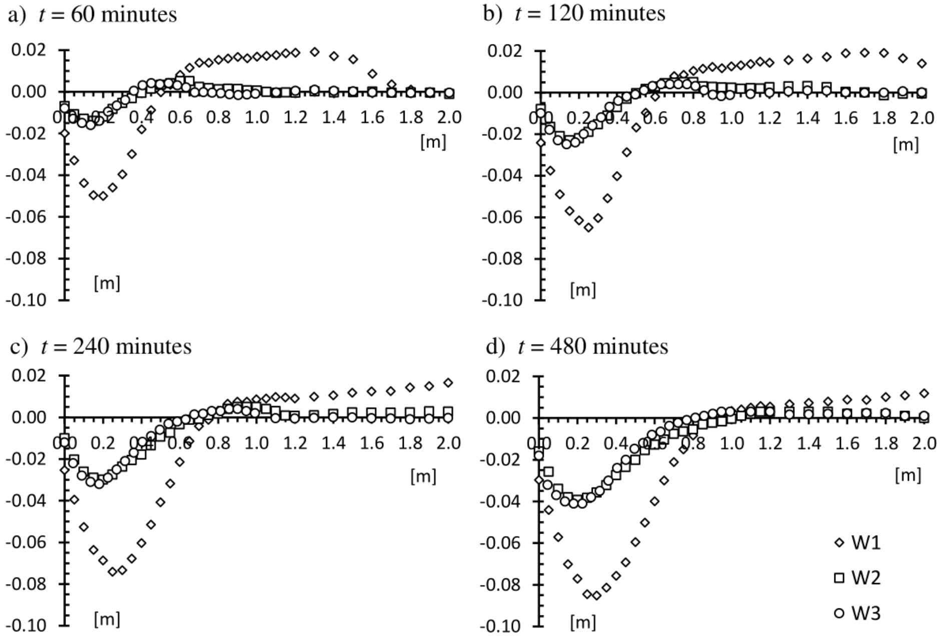


Fig. 6. Profiles of scour after t time duration of flow rate $q = 0.0466\ \mathrm{m^2s^{-1}}$

Figure 7 illustrates the variability of the maximum local scour hole depth h_{max} during the flow on the model. The maximum depth of the scour formed after 480 minutes (fig. 7) of flow duration for the tested range of flow rates on model W2 with baffle blocks was $h_{max} = 0.014 \div 0.039$ m, and on model W3 with rip-rap it changed within the range $h_{max} = 0.026 \div 0.040$ m. This scour hole was smaller than the bottom depth formed on the W1 model, with a flat, horizontal starting plate, for which $h_{max} = 0.041 \div 0.065$ m. The use of baffle blocks in two rows or a rip-rap at the outflow also delayed the scour development in time.

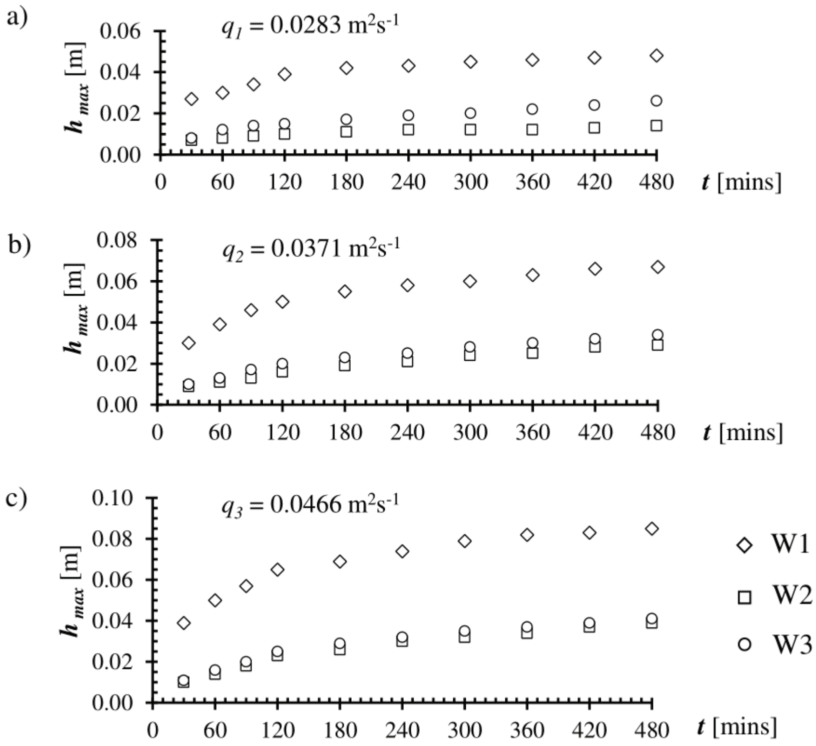


Fig. 7. Variability of scour depth h_{max} versus duration of flow rate: a) $q = 0.0283$ m^{2}s^{-1}, b) $q = 0.0371$ m^{2}s^{-1}, c) $q = 0.0466$ m^{2}s^{-1}

Table 2 summarizes the maximum scour depths of h_{max} measured after different particular discharge duration. It also shows what percentage of the maximum scour hole depth $h_{max(W1)}$ formed on the model with a flat, horizontal bottom slab (W1), the depths $h_{max(W2)}$ and $h_{max(W3)}$ obtained on the model with the use of baffle blocks arranged in two rows (W2) and rip-rap (W3). As a result of using baffle blocks or rip-rap, a significant reduction by half up to one third of the maximum scour depth was obtained. After 480 minutes of flow, this depth on a model with baffle blocks arranged in two rows of $h_{max(W2)}$ constituted (29.2 ÷ 45.9)% of $h_{max(W1)}$ on a model with a flat outflow. The maximum depth of the scour formed at the same time on the model with rip-rap $h_{max(W3)}$ was (48.2 ÷ 54.2)% $h_{max(W1)}$ (Table 2).

Table 2. Maximum depths of scour h_{max} shaped in time t for different energy dissipators: W1, W2, W3

t	$q = 0.0283\ \mathrm{m^2s^{-1}}$			$q = 0.0371\ \mathrm{m^2s^{-1}}$			$q = 0.0466\ \mathrm{m^2s^{-1}}$		
[min]	$h_{max(W1)}$	$h_{max(W2)}$	$h_{max(W3)}$	$h_{max(W1)}$	$h_{max(W2)}$	$h_{max(W3)}$	$h_{max(W1)}$	$h_{max(W2)}$	$h_{max(W3)}$
60	0.030	0.008	0.012	0.039	0.011	0.013	0.050	0.014	0.016
	(100%)	26.7%	40.0%	(100%)	28.2%	33.3%	(100%)	28.0%	32.0%
120	0.039	0.010	0.015	0.050	0.016	0.020	0.065	0.023	0.025
	(100%)	25.6%	38.5%	(100%)	32.0%	40.0%	(100%)	35.4%	38.5%
240	0.043	0.012	0.019	0.058	0.021	0.025	0.074	0.030	0.032
	(100%)	27.9%	44.2%	(100%)	36.2%	43.1%	(100%)	40.5%	43.2%
480	0.048	0.014	0.026	0.067	0.029	0.034	0.085	0.039	0.041
	(100%)	29.2%	54.2%	(100%)	43.3%	50.7%	(100%)	45.9%	48.2%

Modelled energy dissipation devices of: W1 – flat horizontal plate, W2 – double baffle blocks, W3 – rip-rap.

Basing on measurement results of the maximum depth of the h_{max} scour hole and the distance of its occurrence from the end of the reinforced bottom section L_{max}, the values of the ctgβ coefficient after 60, 120, 240 and 480 minutes were calculated on a model with different construction of energy dissipation devices (W1, W2, W3) and are shown in Figure 8.

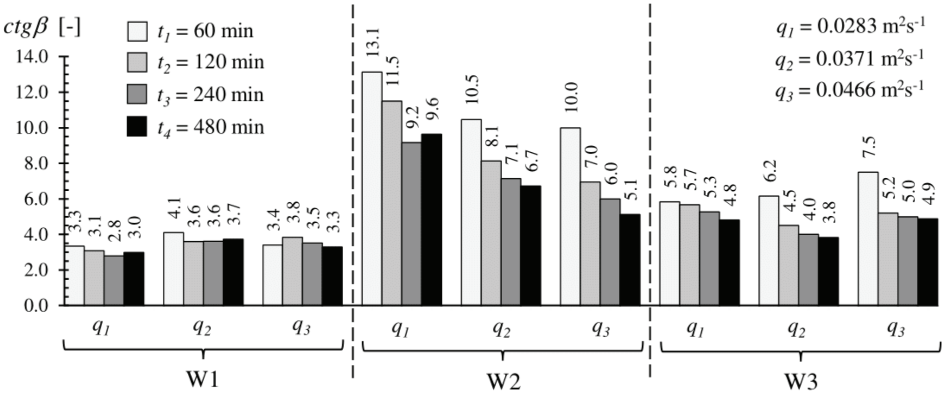


Fig. 8. Variability of ctgβ coefficient values for flow rate q on the model for different energy dissipators: W1, W2, W3

The ctgβ coefficient of the critical line is not a constant value, but should be determined individually for each structure. Its value depends on soil parameters of the ground and dimensions of the foundation and its depth [38]. The obtained values of the coefficient on the ground of the measurement results showed the influence of the applied energy dissipation devices on the development of scouring and at the same time on the safety condition of the object. The smallest values of the ctgβ coefficient, ranging from 2.8 to 4.1, were obtained in the case of a hole formed on the model with a flat, horizontal slab (W1). Moreover, these values slightly decreased with time of scour hole formation. Therefore, due to the shape of the scour, this structure appeared to be the most unfavorable among the tested ones. In this case, the scour was formed closest to the end of the outflow. The shape and location of the local scour was favorably influenced by the application of a rip-rap at the end of the outflow. The values of the ctgβ coefficient increased and ranged from 3.8 to 7.5. The application of this type of reinforcement significantly improves the safety of the object. In the case of using baffle blocks arranged in two rows, the highest values of the analyzed coefficient were obtained, ranging from 5.1 to 13.1, although these values were decreasing with the flow duration. This indicates a progressive development of the building's safety hazard during its operation, due to the progressive scouring of the lower stand.

The degree of stability hazard of the structure being modeled was also assessed based on the criteria described in equations (2.1) and (2.2). The results of the calculations of safety factor limit values; lower ctgβ_d and upper ctgβ_g using equations (2.1) and (2.2) are presented in Figure 9 in the form of lines dividing the chart area into three zones:

- area I, which determines the location of the scour hole outside the impact zone,
- area II defining the state of the security variable,
- area III of the building's stability threatened state due to excessive development of local scouring.

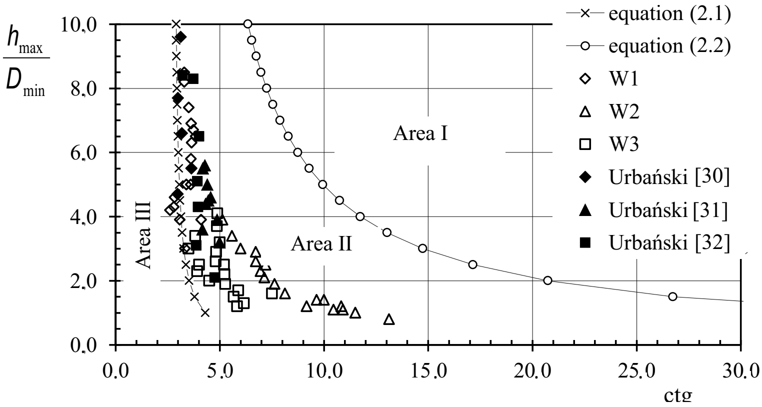


Fig. 9. Limiting and measured values of ctgβ coefficient on a model with different energy dissipation devices (W1, W2, W3)

Figure 9 also presents ctgβ values calculated on the basis of the measured scour dimensions on the model of energy dissipation equipment design W1, W2, W3. In each case studied, a scour hole was created in the area of active zone of the ground. With the use of baffle blocks arranged in two rows (W2) and a rip-rap (W3), the ctgβ coefficient values are located on the diagram in the area II, indicating the state of variable safety. The points corresponding to the ctgβ values obtained on the model with the use of baffle blocks are located closest to the upper safety curve, in the central part of area II, which indicates the lowest stability hazard among the tested variants. The greatest risk of the stability of the modeled structure was posed by the scour following the outflow construction, i.e. in the form of a flat, horizontal slab (W1). The points, in this case, are located in the direct vicinity of the boundary curve ctgβ_d and in area III. Similar results (Fig. 9) were obtained in Urbański's research [30-32] on a model of the structure with gated check equipped with energy dissipation basin, where at subsequent research stages also a stone rip-rap and chicanes were used downstream the gate. For experimental studies carried out with the dosing of sediment, the safety factor demonstrated much higher values than without filling the material [38].

5. CONCLUSIONS

The analysis of the results of experiments carried out on the sluice gate model, which aimed at recognizing the impact of the design of energy dissipation devices on the size of local bed scouring and structure safety, led to the following conclusions:

1) The greatest bottom scour holes, both in terms of depth and length, occurred on the structure model with energy dissipation devices in the form of a flat, horizontal slab. The hole in this case developed the fastest, and its shape and size posed the greatest threat to the stability of the structure. The obtained values of the safety coefficient ctgβ were close to the lower limit value or did not reach it, which indicates the direct occurrence of a state of danger for the stability of the structure associated with the excessive development of scouring.

2) The use of double-row baffle blocks or rip-rap at the end of the outflow part significantly reduced the amount of local scour dimensions and delayed the bed erosion over time, in comparison with the same process on a model with a flat, horizontal outflow slab. The maximum depth of the scour hole after 480 minutes of flow on a two-row baffle blocks model was 29.2 ÷ 45.9% of the maximum scour depth shaped behind the flat bottom of the outflow.

3) Considering building safety, the most favorable solution among the modeled energy dissipation devices were chicanes arranged in two rows. In this case, the smallest scouring was obtained, and the shape of the hole did not directly threaten the stability of the modeled structure.

4) However, the values of the coefficient of safety line inclination ctgβ were decreasing over time simultaneously with local scour deepening, which indicates an increase in the safety hazard of the structure in the long term. Therefore, the assessment of the structure's foundation scouring hazard should also be conducted on the basis of direct field measurements.

REFERENCES

1. S. Pisarczyk, „Fundamentowanie dla inżynierów budownictwa wodnego”, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, pp.448, 2012.
2. S. Bajkowski 2007. „Proste kryteria oceny bezpieczeństwa jazów na rzekach nizinnych”, Infrastruktura i Ekologia Terenów Wiejskich, 4(2), PAN, Oddział w Krakowie, 7–14. 2007.
3. J. Urbański, L. Hejduk, „Analiza rozmiarów lokalnego rozmycia powstałego po wystąpieniu wezbrania”. Monografia KGW-PAN, z. XX, tom 1, 389-400, 2014.
4. K. I. Rossinskij, „Hydraulic of scouring pits” Chapter 2: “Problems of river runoff control”, Acad. Sci. USSR. Section for Scientific Study of Water Engineering Problems, 1961.
5. H. N. C. Breusers, „Time Scale of Two Dimensional Local Scour”, Proceedings of 12th Congress of IAHR, Fort Collins, USA, vol. 3: 275 – 282, 1967.
6. K. I. Rossinskij, I. A. Kuzmin, „Opyt projektirovanija miestnych razmyvov v nižnich bjefach gidrouzlov”, “Rabota nižnich biefov gidrotechničeskich sooruženij”, Kolos, Moskva. 96 – 107, 1969.
7. A. Żbikowski, „Badania laboratoryjne zależności głębokości rozmycia poniżej przelewu od długości umocnień i czasu trwania doświadczenia”, Maszynopis, Biblioteka Politechniki Warszawskiej, Warszawa, 1970.
8. K. S. Popova, „Raschet izmenenia glubiny mestnyh razmyvov za plotinami vo vremeni”, Izv. VNNIG 119: 66 – 73, 1985.
9. R. Błażejewski, „Prognozowanie rozmyć miejscowych gruntów niespoistych poniżej budowli upustowych”, Rocznik Akademii Rolniczej w Poznaniu, Rozprawy naukowe, Zeszyt 190, Wyd. AR w Poznaniu, 1989.
10. Sz. L. Dąbkowski, P. Siwicki, „Analiza głębokości rozmycia koryta na modelach jazu”, Scientific Review Engineering and Environmental Sciences, (19): 39 – 50, 2000.
11. S. Pagliara, S. M. Kurdistani, „Scour downstream of cross-vane structures”, J. of Hydro-Environment Res., 7(4), 236–242, 2013.
12. Sz. L. Dąbkowski, J. Skibiński, A. Żbikowski, „Hydrauliczne podstawy projektów wodnomelioracyjnych”, Państwowe Wydawnictwo Rolnicze i Leśne, Warszawa, 457 – 517, 1982.
13. G. J. C. M. Hoffmans, H. J. Verheij, „Scour Manual”, Balkema, Rotterdam, the Netherlands, pp. 193, 1997.
14. N. Rajaratnam, B. Berry, „Erosion by circular turbulent wall-jets”, J. Hydr. Res., 15 (3): 277 – 289, 1977.
15. G. J. C. M. Hoffmans, R. Booij, „The influence of upstream turbulence on local scour holes”, Public Works and Water Mgmt., Road and Hydr. Eng. Div., Delft, The Netherlands, 1993.
16. G. J. C. M. Hoffmans, K. W. Pilarczyk, „Local Scour Downstream of Hydraulic Structures”, Journal of Hydraulic Engineering ASCE, 121 (4): 326 – 340, 1995.
17. S. Wu, N. Rajaratnam, „Transition from hydraulic jump to open channel flow”, Journal of Hydraulic Engineering 122, 9: 526 – 528, 1996.
18. J. Urbański, „Wpływ turbulencji strumienia na rozmiary lokalnego rozmycia na modelu jazu”, Acta Scientiarum Polonorum Architectura, 07 (2): 3 – 12, 2008.
19. H. Zobeyer, N. Jahan, Z. Islam, G. Singh, N. Rajaratnam, „Turbulence characteristics of the transition region from hydraulic jump to open channel flow”, J. of Hydr. Res., 48, 3: 395 – 399, 2010.
20. C. Manes, M., Brocchini, „Local scour around structures and the phenomenology of turbulence”, J. Fluid Mech., 779, 309-324, 2015.
21. N. B. Rustiati, V. Dermawan, Rispiningtati, L. M. Limantara, “The influence of sandy clay bed material to local scour behavior”, Journal of Water and Land Development, 35, 193–202, 2017.

22. D. Guan, B. Melville, H. Friedrich, „Flow patterns and turbulence structures in a scour hole downstream of a submerged weir", J. of Hydr. Eng., 140(1), 68–76, 2014.
23. S. O. Lee, S. H. Hong, „Turbulence characteristics before and after scour upstream of a scaled-down bridge pier model", Water 11(9), 1900, 2019.
24. O. A. Karim, K. H. M. Ali, „Prediction of flow patterns in local scour holes caused by turbulent water jets", J. Hydr. Res., 38, (4): 279 – 287, 2000.
25. J. Urbański, P. Siwicki, „Zastosowanie programu CFD Fluent do obliczeń charakterystyk turbulencji strumienia w dolnym stanowisku jazu", Infrastructure and Ecology of Rural Areas, PAN, Oddział w Krakowie 4/2: 201 – 209, 2007.
26. P. Siwicki, „Numeryczne modelowanie rozmyć poniżej budowli piętrzących", Scientific Review Engineering and Environmental Sciences, Issue 2(40): 155 – 168, 2008.
27. T. R. Al-Husseini, A. S. T. Al-Madhhachi, Z. A. Naser, "Laboratory experiments and numerical model of local scour around submerged sharp crested weirs". Journal of King Saud University – Engineering Sciences 32, 167–176, 2020.
28. F. Lee, J. Lai, Y. Lin, K. Chang, X. Liu, Ch. Huang, "Prediction of Bridge Pier Scour Depth and Field Scour Depth Monitoring". E3S Web of Conferences. 40. 03007, 2018.
29. M. Chandara, Z. Genguang, H. Vouchleang, Z. Shuang, F. Yulin, "Assessment of Turbulence Models on Bridge-Pier Scour Using Flow-3D", World Journal of Engineering and Technology, 7(2), 241-255, 2019.
30. J. Urbański, „Rozmycia dna na modelu jazu ze zmienną długością umocnień w dolnym stanowisku", Acta Scientiarum Polonorum Architectura 6 (2): 27 – 36, 2007.
31. J. Urbański, „Wpływ szorstkości umocnień w dolnym stanowisku jazu na lokalne rozmycia dna", Scientific Review Engineering and Environmental Sciences, Issue 2(40): 169 – 177, 2008.
32. J. Urbański, „Eksperymentalne badania wpływu szykan wbudowanych na wypadzie jazu na wielkość rozmyć miejscowych", „Bezpieczeństwo zapór – bezpieczeństwo ludności i środowiska" (pod red. W. Jankowskiego i A. Wity), Seria: Monografie Instytutu Meteorologii i Gospodarki Wodnej, IMGW, Warszawa, 185 – 194, 2009.
33. G. Oliveto, V. Comuniello, „Local Scour Downstream of Positive-Step Stilling Basins", J. of Hydr. Eng. 135(10): 846 – 851, 2009.
34. M. A. Hossam, M. E. G. Mohamed, M. H. M. Ahmed, A. M. A. Abdel, S. F. A Fahmy, "Minimizing downstream scour due to submerged hydraulic jump using corrugated aprons", Ain Shams Engineering Journal, 5, 1059–1069, 2014.
35. H. Hamidifar, M. Nasrabadi, M. H. Omid, "Using a bed sill as a scour countermeasure downstream of an apron", Ain Shams Engineering Journal 9,1663–1669, 2018.
36. E. A. Elnikhely, I. Fathy, "Prediction of scour downstream of triangular labyrinth weirs", Alexandria Engineering Journal, 59(2),1037–1047, 2020.
37. Rozporządzenie Ministra Środowiska z dn. 20 kwietnia 2007 r. w sprawie warunków technicznych, jakim powinny odpowiadać budowle hydrotechniczne i ich usytuowanie (Dz. U. Nr 86, poz. 579).
38. S. Bajkowski, P. Siwicki, J. Urbański, „Wykorzystanie badań laboratoryjnych rozmyć poniżej budowli wodnych do oceny ich bezpieczeństwa", Acta Scientiarum Polonorum Architectura, 1-2: 41–51, 2002.
39. Z. Hong, Z. Hongyan, D.Jianke. 2012. "Nonlinear static analysis of an asphalt concrete core dam for Comparison of three constitutive models", Archives of Civil Engineering, LVIII, 4, 2012. Doi: 10.2478/V.10169-012-0027-7.
40. A. Duchaczek, D. Skorupka. "Evaluation of probability of bridge damage as a result of terrorist attack", Archives of Civil Engineering, LIX, 2, 2013. Doi: 10.2478/Ace-2013-0011.
41. T. Bladyniec, „The history of the railway bridges by the citadel in Warsaw", Archives of Civil Engineering, LXV, 1, 2010. Doi: 10.2478/ace-2019-0011.
42. J. Szer, "Safety of buildings and construction disasters" Archives of Civil Engineering, LXVI, 1, 2020. Doi: 10.24425/ace.2020.131788.

LIST OF FIGURES AND TABLES:

Fig. 2. Schema of the research models: a – the structure model and analyzed parameters of local scour, b – variant constructions of energy dissipation devices, c – dimensions of baffle blocks [cm]

Rys.2. Schemat stanowiska badawczego: a – model budowli oraz analizowane parametry rozmycia, b – wariantowe konstrukcje urządzeń do rozpraszania energii, c – wymiary szykan [cm]

Fig 3. Granulation curves: 1 – bed sediment, 2 – rip-rap

Rys. 3. Krzywe uziarnienia: 1 – rumowisko denne, 2 – narzut kamienny

Fig. 4. Profiles of scour after *t* time duration of flow rate $q = 0.0283\ \mathrm{m^2s^{-1}}$

Rys. 4. Profile rozmycia po czasie *t* trwania przepływu o natężeniu $q = 0{,}0283\ \mathrm{m^2s^{-1}}$

Fig. 5. Profiles of scour after *t* time duration of flow rate $q = 0.0371\ \mathrm{m^2s^{-1}}$

Rys. 5. Profile rozmycia po czasie *t* trwania przepływu o natężeniu $q = 0{,}0371\ \mathrm{m^2s^{-1}}$

Fig. 6. Profiles of scour after *t* time duration of flow rate $q = 0.0466\ \mathrm{m^2s^{-1}}$

Rys. 6. Profile rozmycia po czasie *t* trwania przepływu o natężeniu $q = 0{,}0466\ \mathrm{m^2s^{-1}}$

Fig. 7. Variability of scour depth h_{max} versus duration of flow rate: a) $q = 0.0283\ \mathrm{m^2s^{-1}}$, b) $q = 0.0371\ \mathrm{m^2s^{-1}}$, c) $q = 0.0466\ \mathrm{m^2s^{-1}}$

Rys. 7. Zmienność maksymalnej głębokości rozmycia h_{max} w czasie *t* trwania przepływu: a) $q = 0{,}0283\ \mathrm{m^2s^{-1}}$, b) $q = 0{,}0371\ \mathrm{m^2s^{-1}}$, c) $q = 0{,}0466\ \mathrm{m^2s^{-1}}$

Fig. 8. Variability of ctgβ coefficient values for flow rate *q* on the model for different energy dissipators: W1, W2, W3

Rys. 8. Zmienność wartości współczynnika ctgβ dla przepływu q na modelu o różnej konstrukcji urządzeń do rozpraszania energii: W1, W2, W3

Fig. 9. Limiting and measured values of ctgβ coefficient on a model with different energy dissipation devices (W1, W2, W3)

Rys. 9. Wartości graniczne i pomierzone współczynnika ctgβ na modelu o różnej konstrukcji urządzeń do rozpraszania energii (W1, W2, W3)

Tab. 1. Hydraulic flow parameters in model experiments

Tab. 1. Hydrauliczne parametry przepływu w doświadczeniach na modelu

Tab. 2. Maximum depths of scour h_{max} shaped in time *t* for different energy dissipators: W1, W2, W3

Tab. 2. Maksymalne głębokości rozmycia h_{max} ukształtowane w czasie *t* na modelu o różnej konstrukcji urządzeń do rozpraszania energii: W1, W2, W3

WPŁYW KONSTRUKCJI URZĄDZEŃ DO ROZPRASZANIA ENERGII NA ROZMIARY MIEJSCOWYCH ROZMYĆ DNA NA MODELU ŚLUZY

*Słowa kluczowe***:** rozmycia lokalne. hydrauliczne badania modelowe, urządzenia do rozpraszania energii, śluza.

W artykule przedstawiono wyniki badań eksperymentalnych, których celem było rozpoznanie wpływu konstrukcji urządzeń do rozpraszania energii na kształtowanie się miejscowych rozmyć dna poniżej śluzy. Doświadczenia przeprowadzono na modelu śluzy zbudowanym w korycie o przekroju prostokątnym i szerokości wynoszącej 0,58m, z wypływem strumienia spod zasuwy piętrzącej na poziome dno o długości 0,80m. Na dnie za zasuwą piętrzącą zastosowano trzy różne konstrukcje urządzeń do rozpraszania energii: płaską, poziomą płytę (W1), płytę z szykanami rozmieszczonymi w dwóch rzędach (W2) i narzut kamienny (W3) o chropowatości względnej w zakresie 0,061÷0,078. Doświadczenia polegały na formowaniu rozmycia w czasie 480 minut przez strumień w dolnym stanowisku na odcinku, gdzie dno koryta wypełnione było piaskiem sortowanym (d_{50}=1,1mm, $(d_{84}/d_{16})^{0,5}$=1,77). Podczas doświadczeń mierzono głębokości rozmycia w profilu podłużnym, w osiowej płaszczyźnie koryta po upływie 30, 60, 90, 120, 180, 240, 300, 360, 420 i 480 minut. Analizowano wpływ konstrukcji urządzeń do rozpraszania energii na parametry charakteryzujące rozmycie pod względem bezpieczeństwa budowli, takie jak głębokość maksymalna rozmycia, odległość wystąpienia największego rozmycia od końca wypadu budowli, kształt wyboju. Są to parametry najczęściej uwzględniane w ocenie skuteczności działania urządzeń do rozpraszania energii w badaniach modelowych. Zastosowano także kryterium wykorzystywane do oceny bezpieczeństwa budowli wodnych, uwzględniające nachylenie prostej przechodzącej przez koniec wypadu i dół rozmycia w miejscu występowania jego maksymalnej głębokości. Obliczono wartości graniczne współczynników nachylenia tej prostej i na ich tle analizowano wartości tych samych współczynników uzyskane w oparciu o wyniki pomiarów na modelu o różnej konstrukcji urządzeń do rozpraszania energii.

Największe rozmycia dna, zarówno pod względem głębokości, jak i długości występowały na modelu śluzy z urządzeniami do rozpraszania energii w postaci płaskiej, poziomej płyty. Wybój w tym przypadku rozwijał się najszybciej, a jego kształt i wielkość stwarzały największe zagrożenie stateczności budowli. Uzyskane wartości współczynnika bezpieczeństwa ctgβ zbliżone były do dolnej wartości granicznej lub jej nie osiągały, co wskazuje na bezpośrednie występowanie stanu zagrożenia stateczności fundamentu budowli, związanego z nadmiernym rozwojem rozmycia. Zastosowanie na odcinku wypadowym szykan rozmieszczonych w dwóch rzędach lub narzutu kamiennego wpływało w znacznym stopniu na ograniczenie rozmiarów rozmycia oraz opóźnianie erozji dna w czasie, w porównaniu z przebiegiem tego procesu na modelu z płaską, poziomą płytą wypadową. Maksymalna głębokość rozmycia po 480 minutach trwania przepływu na modelu z szykanami w dwóch rzędach stanowiła 29,2 – 45,9% głębokości maksymalnej wyboju ukształtowanego za wypadem płaskim. Z punktu widzenia bezpieczeństwa budowli najkorzystniejszym rozwiązaniem spośród modelowanych urządzeń do rozpraszania energii były szykany rozmieszczone w dwóch rzędach. W tym przypadku uzyskano rozmycia o najmniejszych rozmiarach, a kształt tworzącego się wyboju nie stwarzał bezpośrednio zagrożenia stateczności modelowanej budowli. Jednak wartości współczynnika nachylenia prostej bezpieczeństwa były malejące w czasie, co wskazuje na wzrost zagrożenia bezpieczeństwa obiektu związany z rozwojem rozmycia lokalnego w dłuższym okresie jego eksploatacji.

Received: 16.06.2020, Revised: 29.09.2020