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Original Article

Internal Energy Dissipator in Highway Steep Box Culverts - Effectiveness of Roughness Elements at the End Part of the Culverts

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Abstract *- In the hydraulic design of steep highway culverts in mountainous areas, in addition to determining the size of culverts to drain the design discharge, the design of energy dissipators in the culvert body to reduce the size of the dissipators downstream of the culverts is also considered. Currently, in Vietnam, single broken-back culverts consisting of a steeper portion near the inlet and a followed mild slope section may be used as an internal energy dissipator for steep highway culverts or culverts as straight drops. In this study, a physical model was built by producing roughness elements at the end of the culverts to dissipate the outlet velocities with high energy. The study showed that the roughness elements played an important role in dissipating the flow energy at the outlet, remarkably, when the culvert slope ranged from 5% to 13%, and the proposal roughness elements reduced energy by over 50%.*

Keywords *- Roughness elements, Box culverts, Reduce flow velocity, Energy dissipator.*

1. Introduction

Due to the steep terrain, the solution to design and build steep culverts is often set out in construction projects delivered in Vietnam's midland and mountainous areas. Some traffic construction projects built in recent years as examples: The road project connecting Noi Bai - Lao Cai highway to Sa Pa town has 14 steep culverts /22km of the road; Ha Long - Van Don Expressway Project, section Km7+000 -:- Km14+000 has 16 steep culverts/7km of road, Knowing that open flow in the culvert is also a form of flow on the water slope. The flow energy downstream of the culvert is very large. It is necessary to build energy dissipation works to reduce the risk of erosion downstream. In fact, downstream of the culvert may not be able to build energy dissipation works due to lack of space (there have been/will have other construction works downstream, or the topographical conditions are not enough for construction), or must construction of large-sized energy-dissipating works, this requires a solution to consume flow energy right in the culvert body. In Vietnam, there have been a number of energy dissipation solutions in the culvert body applied in the construction of traffic works as follows:

1) Arrangement of a culvert in a uniformly sloping step [1-3] (Fig. 1). This type of drain has many advantages: relatively good ability to dissipate energy; unnecessary to build energy dissipation facilities downstream of culverts; higher anti-slip stability than a sloping culvert placed on an inclined plane. The disadvantages of this type of culvert are: It is challenging to ensure waterproof conditions between the culvert steps; Reduces the culvert clearance height.

2) Arrangement of broken culverts with small slopes in the downstream section [1-2], [4], [5-7] (Fig. 2). The advantages of this culvert layout are Relatively simple in construction; Suitable to both circular culverts and box culverts; Unchanged culvert clearance height; Increased slip resistance compared to culverts placed on a slope. However, the arrangement of this type of culvert gives the ability to consume less energy in the slope body.

In addition to the two solutions for arranging culverts to dissipate energy as above, there are other solutions to dissipate energy in the body of the culvert as follows:

3) Arrange an additional dissipation wall at the second culvert section with a small slope [4], [8], [9] (Fig. 3). This solution creates the phenomenon of water jumping near the outlet of the culvert so that it will increase the efficiency of high energy dissipation. But there are many disadvantages: The design and layout of the horizontal culvert are relatively difficult in the condition of terrain with a steep slope; it only produces jumps under suitable flow conditions; When there is a phenomenon of strong water jumping, it can make

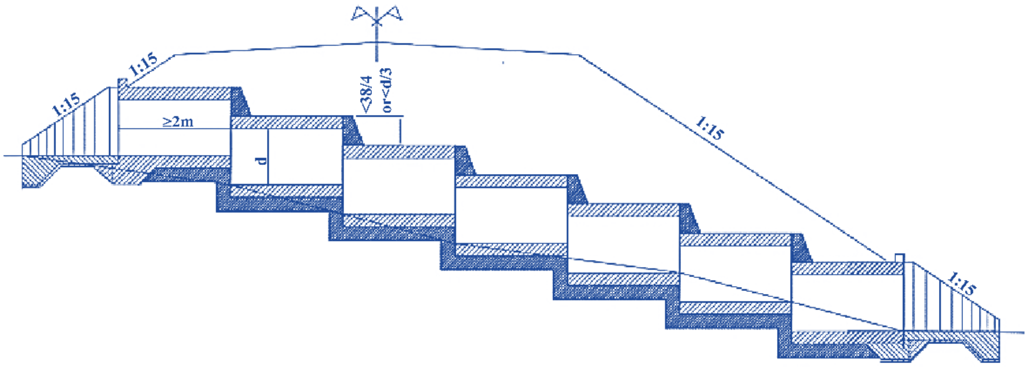

Fig. 1 Sloped culverts arranged in a uniformly sloping step.

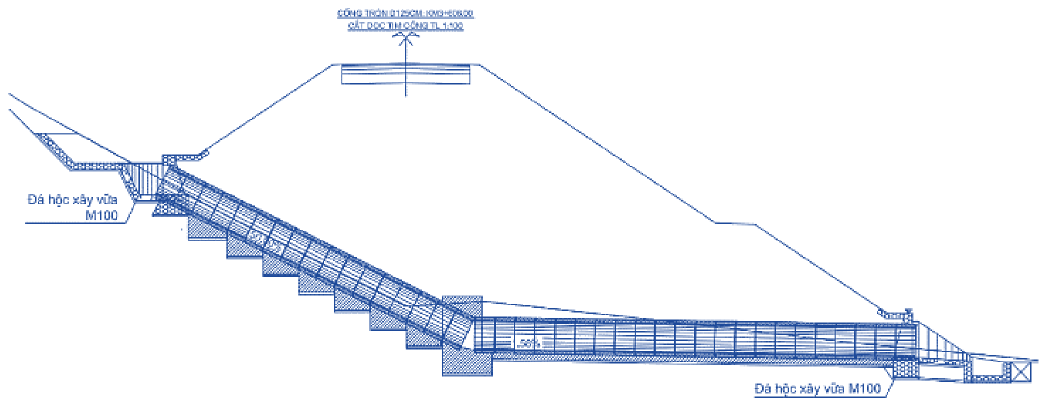

Fig. 2 Slope culvert arranged in the type of inclined plane with two slopes

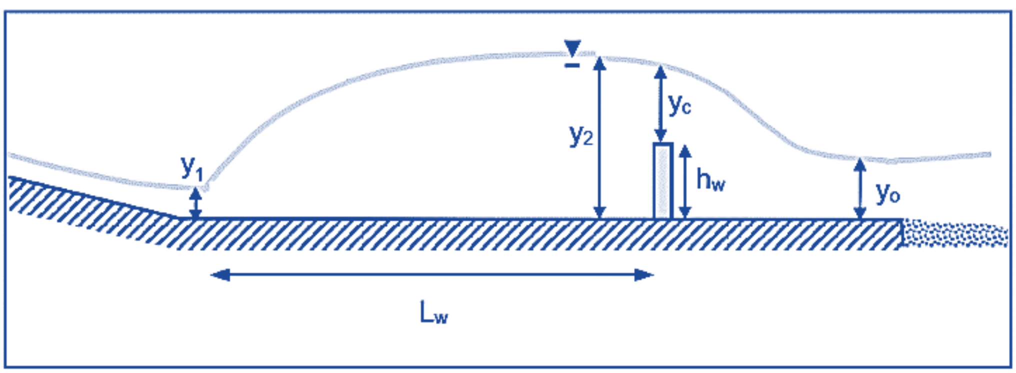

Fig. 3 Dissipative wall arrangement near the outlet of the box culvert [4]

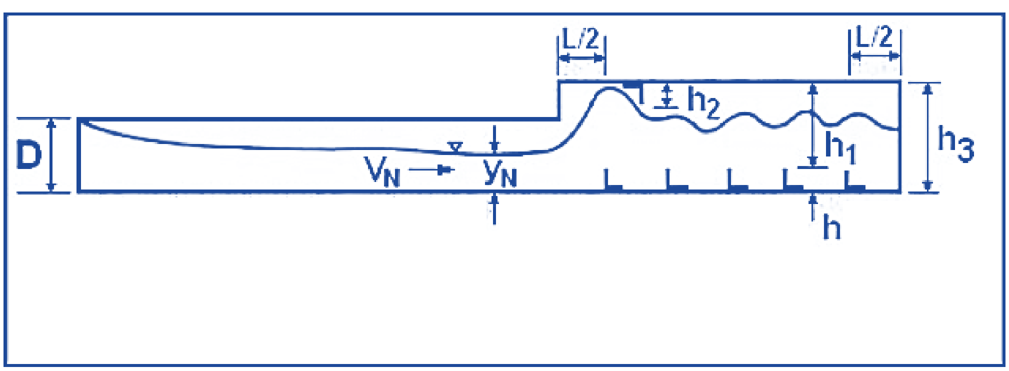

Fig. 4 Water jumping at the end of the culvert when arranging rough roughness elements [4]

the depth after the water jump larger than the height of the culvert, causing the flow regime in the culvert to change; Relatively complicated in construction.

4) Arrange reinforcement roughness elements near the outlet of the culvert [4-5], [11], [12], (Fig. 4). This solution has advantages: Relatively simple in construction; High efficiency of power dissipation; Not large roughness element height will not reduce the culvert height much; Can be applied to both round culvert and box culvert. The main disadvantage is that when the culvert is located in an area with mud and rock floods, it is possible to partially deposit sand and rock in the rough roughness element area, leading to reduced energy efficiency and difficulty in maintenance works.

Among the types of energy dissipation in the culvert body mentioned above, the slope culvert with the arrangement of reinforced rough roughness element at the end of the culvert has been widely applied in the world; many advantages (easy construction, high efficiency, does not reduce the drainage capacity of culverts), but this problem has not been studied and applied to the construction of culvert works on roads in Vietnam. In this paper, the author presents the research results on the application of energy dissipation in sloping culverts by arranging reinforced harsh roughness elements in the downstream section of box culverts on roads.

2. Experimental Study of the Physical Model of Energy Reduction by Reinforced Roughness Element in T\the Box Culvert Body

Dissipation of flow in open channels with steep slopes by reinforced roughness element system has been studied by authors worldwide since the 50s of the 20th century. Mohanty (1959), Mohanty and Peterson (1960) [11], and Morris (1968, 1969) [21] studied the arrangement of reinforcing roughness elements at the end of box culverts and open ditches at Virginia Polytechnic Institute. Or the recent studies of F Yousefi, J Mozaffari, S A M Movahed (2019) [14], J. George et al. (2010) [15], Y. Dilrooban et al. (2014) [16], P Fošumpaur, et al. (2019) [17], ...

In Vietnam, a reinforced roughness element is also applied on water slopes following flood drainage works of reservoirs. Le Van Nghi (2013) [18] studied a hydraulic experimental model with the solution of using reinforcement roughness to increase the flow energy consumption on the slope body and reduce the flow energy at the slope end section to reduce the load on the drainage tank of the Ngan Truoi flood spillway (Ha Tinh, Vietnam).

Along with the study of energy dissipation in open channels on steep slopes, the problem of flow energy dissipation in box culverts by reinforced roughness element systems has also been studied by many worldwide authors since the 50s of the 20th century. Mohanty (1959), Mohanty and Peterson (1960) [11], Morris (1968, 1969) [21].

James M. Wiggert et al. (1971) [10] proposed the arrangement of roughness elements in a donut in a circular culvert with a steep slope. A. L. Simon et al. [5] studied energy reduction solutions in circular culverts with two slopes, the second section slope being zero without arranging 03 rough roughness elements in the shape of an annular. A. Bushra and Noor Afzal (2006) [20] studied the arrangement of rough roughness elements in round culverts and U-shaped open channels.

2.1. Basis of the calculation of energy consumption

When the culvert has no roughness element (flat bottom) with a relatively large bottom slope, the flow in the culvert is fast and has a high flow rate and high flow energy. When the roughness element is arranged in the culvert, due to the influence of the rough roughness element, it will create the phenomenon of water jumping in the culvert (when the roughness element height is large enough); jumping water is the solution to consuming a large flow of energy.

Energy dissipation efficiency:

$$\Delta E = \frac{E_1 - E_2}{E_1}.100\% \qquad (1)$$

where E_1 and E_2 are specific energy of a flow referred to as the culvert bed without roughness elements and with roughness elements,

$$E_1 = h_1 + \frac{V_1^2}{2g} \qquad (2)$$

$$E_2 = h_2 + \frac{V_2^2}{2g} \qquad (3)$$

h_1, V_1 is depth, and average velocity flow referred to the culvert bed without roughness elements;

h_2, V_2 are depth, and average velocity flow referred to the culvert bed with roughness elements.

2.2. Set up an Experimental Model

The experiment was carried out at the Laboratory of Hydraulics, the University of Transport - Campus in Ho Chi Minh City (UTC2), experiment with different roughness element heights

2.2.1. Hydraulic Laboratory Glass Flume System

The experiment glass flume system is a recirculating flume system that can change the slope with the diagram shown in Figure 5. The basic parameters of the experiment glass flume system are given in Table 1.

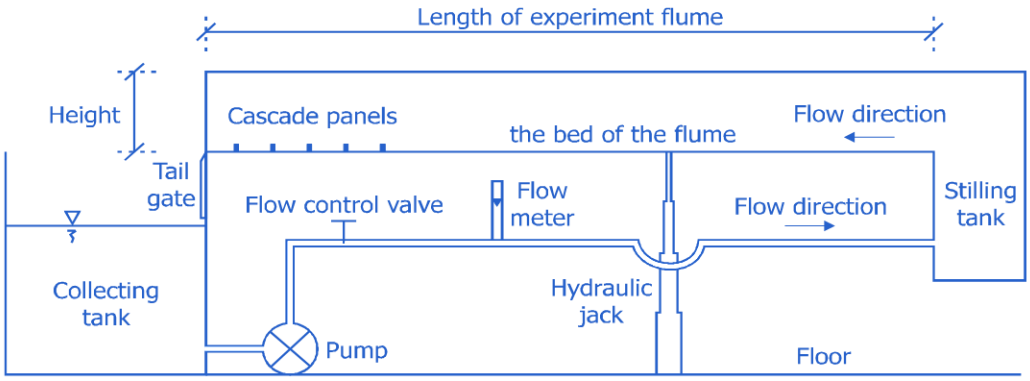

Fig. 5 General scheme of the experiment flume (not in scale).

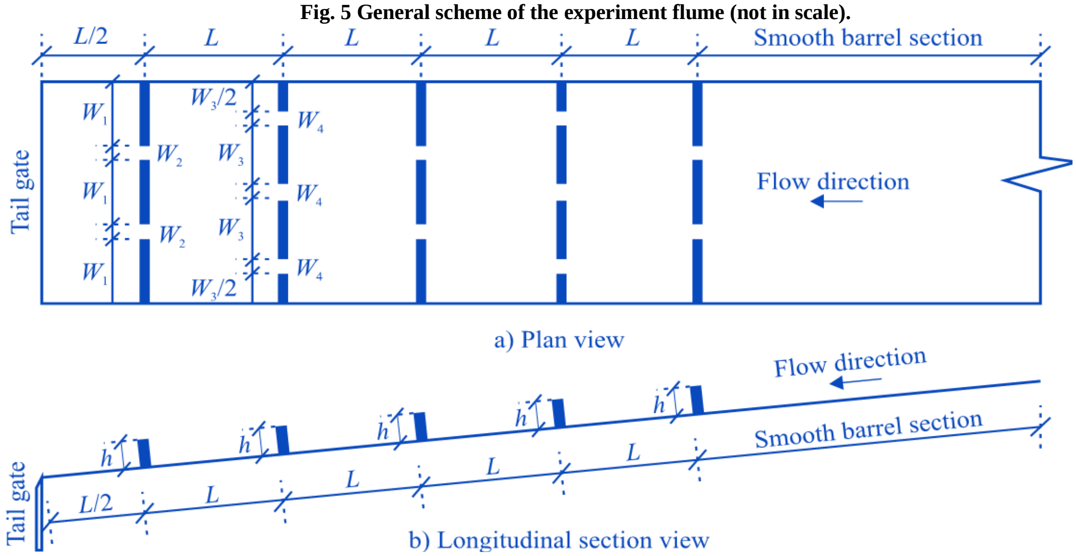

Fig. 6 Staggered roughness elements used in the test (not in scale)

2.2.2. Reinforced Roughness Element Model

Experiments were carried out with the gapless and gapless roughness element model to examine the effectiveness of roughness elements in reducing flow kinetic energy. The experiment aims to determine the reasonable roughness element height and conduct experiments on a roughness element model with different heights. The number of roughness elements is constant at 5 to ensure periodic and stable jumping water. The basic dimensions of the reference roughness element according to HEC-14 are shown in Tables 2. and Fig. 6.

2.3. Experiment Sequence

Installation of the experimental model includes: attaching the rough roughness element to the bottom of the glass trough, ensuring no water leakage, and creating the necessary slope for the model. After installing the model, turn on the pump to create a flow through the experimental model; the flow will be stable after about 5 minutes. Then conduct experiments with the following contents: 1) Observe and photograph the flow in the glass trough; 2) Measure (or check) the pump's flow; 3) Measure the depth of flow along the glass trough (particular attention should be paid to monitoring areas with reinforced roughness elements).

a)

b)

Fig. 7 Experimental image

3. Results and Discussion

3.1. Experiment Results

Observation of the flow in the experimental trough shows that: upstream of the water surface slope is almost horizontal, to the flat culvert section (no rough roughness element) forming the lower water line S2, at the end of the flat sloping culvert, the flow is obstructed by rough roughness elements to form jumping water in the rough roughness element area (Fig.7). Thus, the formation of jumping water at the end of the sloped culvert with rough roughness element is the main factor causing the flow energy to be dissipated. The experimental results are given in Table 3, and the results of the calculation of deceleration and energy are shown in Table 4 and Figure 8, Figure 9

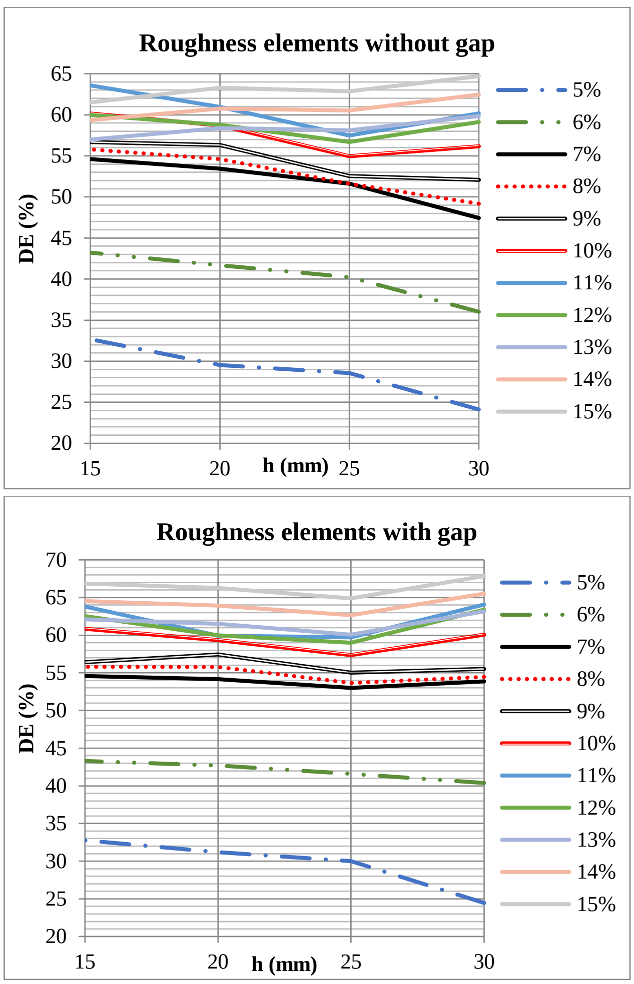

Fig. 8 Comparison of test energy reduction with slope and reinforcement roughness element height

3.2. Analysis and Discussion

In the experimental cases, there is a connection between jumping water between the flow section on the flat bottom and the section with rough roughness elements, so it can be said that jumping water is the leading cause of the decrease in velocity and energy of the water—flow on culverts with reinforced roughness elements.

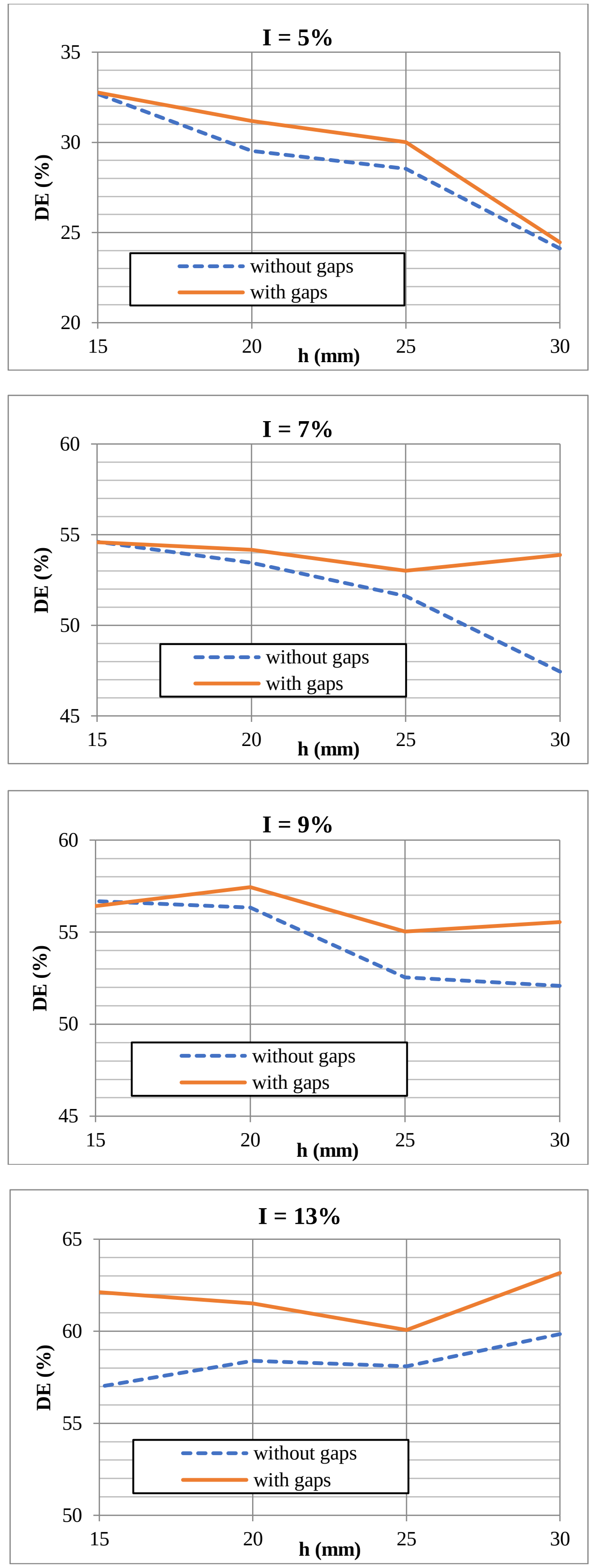

Fig. 9 Comparison of test energy reduction with height and reinforcement roughness element form

When there is a reinforced roughness element, the energy reduction compared to the case without a roughness element is very different: the minimum energy reduction is 24.1% (h = 30mm, gapless roughness element and I = 5%) increase up to 67.9% (h = 30mm, gap roughness element and I = 15%). The average unit energy reduction in all experimental cases was 54.5%.

When the slope of the culvert is larger, the unit energy reduction increases (Fig. 8): with a slope of 5%, the average unit energy reduction is 29.2%; 7% - 52.8%; 9% - 53.3%; 11% - 61.2%; 15% - 64.8%.

The gap roughness elements have a greater energy reduction efficiency than the gapless roughness elements (55.6% and 53.4%, respectively) (Fig. 9).

Table 1. Configuration details of the flume at the laboratory

Parameters	Symbols	Value	Unit
Maximum flow rate	Q_{max}	60	m^3/h
Hydraulic flume width	B	280	mm
Hydraulic flume length	L	7500	mm
Hydraulic jack maximum lifting height	h_{jack}	350	mm
Distance from hydraulic jack to tailgate	L_{jack}	6250	mm
Flow rate observation		Venturi meter	
Water depth observation		Pointer gauge and HM 162.52	

Table 2. Dimensions of test roughness elements

Parameter	Symbols	Value				Unit
Hydraulic flume width	B	280	280	280	280	mm
Roughness elements height	h	30	25	20	15	mm
Gap width	W_2	15	12.5	10	7.5	mm
Roughness elements width	W_1	81.7	83.3	85.0	86.7	mm
	W_3	76.7	79.2	81.7	84.2	mm
	$W_3/2$	38.3	39.6	40.8	42.1	mm
Distance of roughness elements	L	255÷300	213÷250	170÷200	128÷150	mm

Table 3. Experimental results without roughness elements and with roughness elements of different heights

Slope (%)	Without roughness element	Roughness elements without gap				Roughness elements with the gap			
		30mm	**25mm**	**20mm**	**15mm**	**30mm**	**25mm**	**20mm**	**15mm**
	Average depth (m)								
5	0.039	0.103	0.092	0.089	0.069	0.103	0.087	0.083	0.071
6	0.034	0.104	0.091	0.085	0.067	0.090	0.085	0.079	0.069
7	0.030	0.108	0.093	0.084	0.069	0.081	0.086	0.079	0.068
8	0.029	0.108	0.099	0.085	0.077	0.086	0.090	0.077	0.066
9	0.028	0.103	0.101	0.084	0.081	0.088	0.091	0.072	0.061
10	0.027	0.102	0.107	0.091	0.081	0.082	0.097	0.087	0.070
11	0.026	0.101	0.112	0.097	0.081	0.076	0.103	0.102	0.079
12	0.026	0.103	0.113	0.105	0.099	0.079	0.104	0.099	0.086
13	0.026	0.098	0.106	0.104	0.110	0.076	0.097	0.089	0.085
14	0.025	0.098	0.107	0.106	0.112	0.077	0.097	0.090	0.086
15	0.024	0.100	0.109	0.107	0.115	0.078	0.099	0.091	0.087
	Average velocity (m/s)								
5	1.532	0.572	0.643	0.665	0.864	0.577	0.677	0.713	0.829
6	1.737	0.571	0.654	0.699	0.878	0.658	0.695	0.746	0.864
7	2.006	0.548	0.638	0.707	0.858	0.731	0.686	0.751	0.865
8	2.045	0.550	0.598	0.693	0.772	0.686	0.655	0.771	0.897
9	2.086	0.575	0.584	0.707	0.728	0.671	0.652	0.826	0.970
10	2.192	0.580	0.554	0.654	0.728	0.721	0.611	0.682	0.843
11	2.309	0.586	0.527	0.608	0.728	0.781	0.575	0.580	0.745
12	2.293	0.572	0.522	0.565	0.595	0.752	0.570	0.595	0.691
13	2.276	0.605	0.561	0.568	0.538	0.783	0.612	0.663	0.693
14	2.367	0.604	0.553	0.558	0.528	0.769	0.610	0.658	0.688
15	2.466	0.592	0.543	0.553	0.515	0.759	0.598	0.650	0.680

Table 4. The percent of flow energy reduction with the different heights of roughness elements

Slope (%)	Roughness elements without gap				Roughness elements with the gap			
	30mm	25mm	20mm	15mm	30mm	25mm	20mm	15mm
5	24.1	28.5	29.5	32.7	24.5	30.0	31.2	32.8
6	36.0	40.2	41.7	43.2	40.4	41.6	42.7	43.3
7	47.4	51.6	53.5	54.6	53.9	53.0	54.2	54.6
8	49.2	51.6	54.6	55.8	54.4	53.7	55.8	55.8
9	52.1	52.5	56.3	56.7	55.5	55.0	57.4	56.4
10	56.2	55.0	58.7	60.2	60.1	57.4	59.4	60.9
11	60.2	57.5	60.9	63.6	64.1	59.7	59.9	63.8
12	59.1	56.7	58.8	60.0	63.4	59.0	60.0	62.6
13	59.8	58.1	58.4	57.0	63.2	60.1	61.5	62.1
14	62.5	60.5	60.8	59.4	65.5	62.7	63.9	64.5
15	64.7	62.9	63.3	61.5	67.9	64.9	66.3	66.9

On the influence of the reinforcement roughness element height on the energy reduction:

\+ With the roughness element without gap, when the roughness element height increases from 15mm (h/B = 0.054) to 30mm (h/B = 0.107), the energy reduction efficiency decreases but not much: when h = 15mm (h). /B = 0.054), the average energy reduction is 46.9%; h = 20mm (h/B = 0.071) – 45.9%; h = 25mm (h/B = 0.089) – 44.1% and h = 30mm (h/B = 0.107) – 43.9% (the biggest difference is 2.9%).

\+ Similar to the rough roughness element with the gap, when h = 15mm (h/B = 0.054) - 48.2%; h = 20mm (h/B = 0.071) – 47.0%; h = 25mm (h/B = 0.089) – 46.6% (the biggest difference is 2.6%).

The efficiency of energy dissipation in this study is equivalent to the research results by Nghi, L.V. According to Nghi, L.V., the energy reduction in chute flow using roughness elements was an average of 60.75% and a maximum of 64%.

4. Conclusion

Based on the calculation results of deceleration and energy above, the research team has some conclusions:

- Reinforced roughness element in the culvert body has a great effect on reducing flow energy: the average energy reduction is 54.5%.
- The steeper the slope, the more energy is lost, and the efficiency is high when the slope is greater than 6%.
- With roughness element height equal to 15mm (h/B = 0.054), some experimental results ($I \leq 10\%$) have fast flow ($Fr > 1$) in the reinforced rough area. Therefore, using harsh roughness elements of small height is not recommended because it is unlikely to create the phenomenon of jumping water.
- When the roughness element height changes from h/B = 0.071 to h/B = 0.107 (h/B ≈ 0.1), the power dissipation efficiency is almost unchanged. Therefore, for convenience in culvert design and construction, it is recommended to use rough roughness elements with a height of 1/10 of the culvert width.
- A roughness element with a gap effectively dissipates more energy than a roughness element without a gap. Therefore, using a roughness element with a gap is recommended because of its high energy dissipation efficiency; the gap between the roughness elements will reduce sediment accumulation in the sewer.

Acknowledgements

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