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# Impact of roughness elements on reducing flow velocity at outlets of box culverts

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**Keywords:** flow velocity, roughness elements, box culverts, energy dissipaters

**Abstract.** For culverts on slopes greater than critical, rougher material causes greater depth of flow and less velocity in culverts of equal size. Velocity varies inversely with resistance thus roughness elements resistance is obviously an important factor in reducing velocity at the outlets of culverts on steep slopes to prevent scour in downstream of culverts on roads. The criteria for design directives of new energy dissipaters must provide for sufficient energy dissipation, characterized by simplicity of design, effectiveness of energy dissipation and low construction cost. In this study, two physical models were built with producing roughness elements at the end part of the culverts to evaluate the outlet velocities of high-energy culverts. The results showed that with a slope ranging from 5 % to 13 %, the proposed roughness elements reduce energy dissipation from 48.7 % to 52.9 % for roughness elements without gaps and from 51.6 % to 53.9 % for roughness elements with gaps. This result also indicated that the roughness elements in the sloping box culverts can be used to replace energy dissipater structures in the downstream of the box culverts in the Central region of Vietnam.

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## *1. Introduction*

Culverts are by far the most commonly used channel crossing structures on roads in mountainous or steep regions [1–3]. There is no backwater for very steep channels, but the problem is to avoid erosion from high velocity outfall. The outlet design should be effective in re-establishing tolerable non-erosive channel flow within the right-of-way or within a reasonably short distance below the culvert, and should resist undercutting and washout. Energy dissipaters should be simple, easy to build, economical and reasonably self-cleaning during periods of low flow.

Recently, reducing the flow energy in a channel with a relatively large slope $\left(S > S_c\right)$ has drawn interest of many hydraulic scientists such as F. Yousefi et al. [4], J. George et al. [5], Y. Dilrooban et al. [6], P. Fošumpaur et al. [7], D.F. Peterson and P.K. Mohanty [8], H.M. Morris [9, 10], P.K. Mohanty [11], J.M. Wiggert and P.D. Erfle [12], S. Pagliara et al. [13]. A corrugated or rough bed has been shown to dissipate much more energy than a smooth bed, but the effect of the coarse bed does not increase once a certain level of crushed stone has been reached [14]. In 2013, the research showed that a drainage chute with staggered roughness elements of the two-dimensional bars of rectangular cross section throughout causes considerable reduction of exit velocity in the case of pipes on steep slopes under inlet control and free exit, i.e., flowing partly full [15–18]. A.D. Arpan et al.. The exit Froude number can be reduced to nearly unity. A. Simon et al. [19] placed three circular rings (roughness elements) on the inside perimeter of the culvert near the outlet of model culverts as dissipaters to optimize the design of ring chambers that effectively reduce the outlet velocities of high-energy culverts by producing a hydraulic jump in the ring chamber. Experimental models showed model energy reduction up to 90 %. Thus, the ring chamber design that produces hydraulic jumps is most economical to construct and may be selected without limiting velocity-reducing capacity. R.H. Hotchkiss et al. [20] examined the jump geometry and effectiveness of each type of jump within the culvert barrel without the aid of tailwater for a horizontal apron with an end weir and a drop structure with an end weir to reduce the flow energy at the outlet. Experimental results showed that both simple alternatives are applicable to culverts with approach Froude number from 2.6 to 6.0 and are effective in reducing outlet velocity 0.21 to 2.59 m/s, and energy 6 % to 71 %. S. Song et al. [21] developed a theoretical model to quantify the effect of roughness on fully developed Stokes flow in the pipe. The investigated effects of periodically structured surface roughness upon flow field and pressure drop in a circular pipe show that the ratio of static flow resistivity and the ratio of the Darcy friction factor between rough and smooth pipes are expressed in four-order approximate formulations.

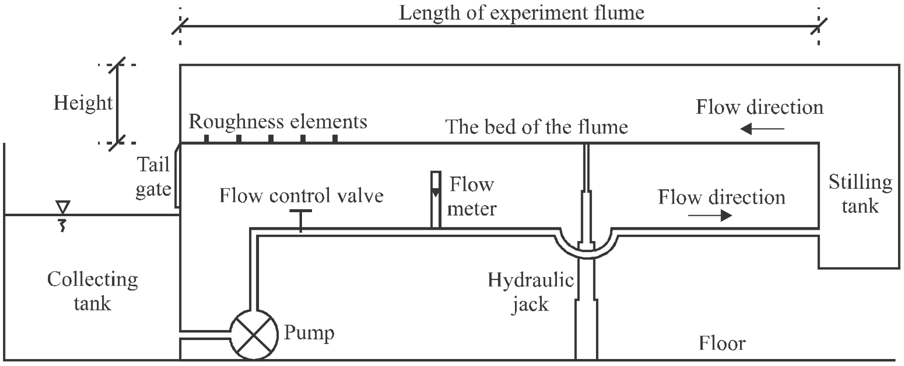
Even though energy dissipation in canals and culverts were studied over some past decades in several countries around the world; however, this topic is still limited in considering local characteristics of Vietnam. In this paper, thus, the main objective is to present the experimental results of the energy dissipation by producing staggered roughness elements of the two-dimensional bars of rectangular cross section at the end part of the box culverts. Box culverts with a relatively large slope ranging from 5 % to 13 % usually found in the midland and mountainous central regions of Vietnam were selected for the experiments and analysis.

## 2. Methods

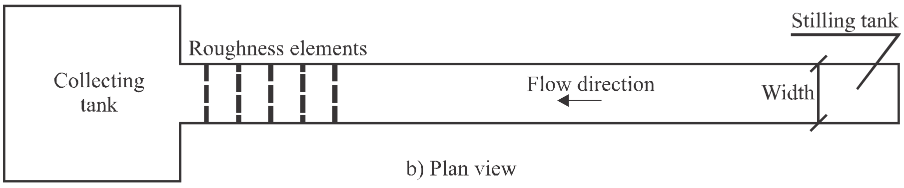
The laboratory work consists of three main steps: setting up physical models, running different scenario models and calculating the hydraulic parameters.

### 2.1. Physical models setup

The first physical model was set up to determine the reasonable range of the roughness elements by placing a different number of roughness elements at the end part of the box culverts. The first physical model was carried out in a current flume 5.0 m long and 0.073 m wide of the Hydraulics – Hydrology Laboratory, University of Transport and Communications (UTC), Hanoi, Vietnam. The length from the flume end to the jack is 3.3 m. The flow meter is a Venturi tube mounted on the water supply pipe. The current flume system can change the slope as showed in Figure 1.



a) Longitudinal section view



b) Plan view

**Figure 1. Schematic view of experimental setup of a flume with variable slope and jacking system (not in scale).**

The second physical model was set up in order to determine the height of the roughness elements after choosing the arrangement of the first stage roughness elements. The second physical model was carried out in a current flume 7.5 m long and 0.28 m wide. Venturi tube mounted on the water supply pipe as shown in Figure 1. This current flume is located in Ho Chi Minh City Campus of UTC.

The main parameters of the experimental flume are shown in Table 1.

***Table 1. Configuration details of the laboratory flume.***

| Parameters | Symbols | Value | | Unit |
|---|---|---|---|---|
| | | Phase 1 (UTC) | Phase 2 (UTC2) | |
| Maximum flow rate | $Q_{max}$ | 8 | 60 | $m^3/h$ |
| Hydraulic flume width | $B$ | 73 | 275 | mm |
| Hydraulic flume length | $L$ | 5000 | 7500 | mm |
| Maximum lifting heigh of hydraulic jack t | $h_{jack}$ | 120 | 350 | mm |
| Distance form hydraulic jack to tail gate | $L_{jack}$ | 3300 | 6250 | mm |
| Flow rate observation | | Venturi meter | Venturi meter | |
| Water depth observation | | Pointer gauge | Pointer gauge | |

These models were constructed at a scale of 1:3.5 to 1:20.5 corresponding to the flow discharge per unit culvert width $q = 0.4 \div 2.8$ $m^3/s/m$ depending on the full-scale application.

In the first physical model, the experiments were conducted with and without roughness elements to examine the effect of roughness on reducing the flow kinetic energy. Two types of roughness element models were made.

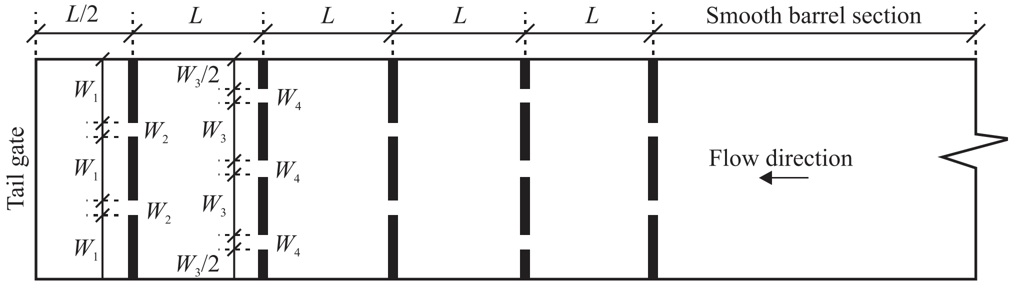
- The first one consists of square shaped roughness elements with height and width of 10 mm with a space distance of 100 mm. These roughness elements are placed perpendicular to the flow (Figure 2).

**Figure 2. Experimental image of first phase**

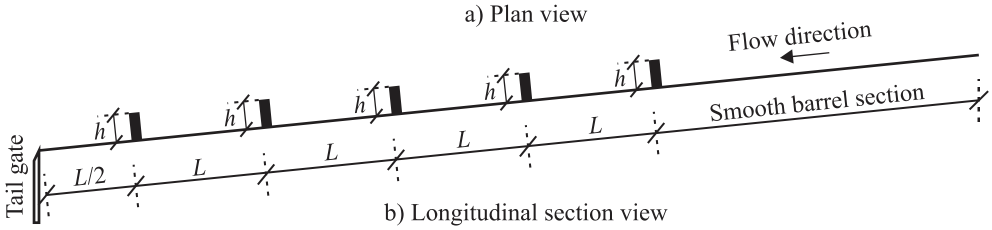
- The second one consists of roughness elements with a gap as shown in detail in Figure 3, with a constant gap length of 0.5 mm; the length of rows of roughness elements with three gaps was 19 mm, while that for rows with two gaps was 21 mm.
- The number of roughness elements installed from the culvert end to upstream was 5, 10, 15, and 20 for both types of roughness elements.

The second physical model was conducted with two types of rectangular shaped roughness elements with and without gaps (Figure 3, Figure 4). The height of roughness elements was 15 mm, 20 mm, 25 mm, and 30 mm, respectively. The detailed structure of roughness elements with a gap is shown in

Table 3. The roughness elements were mounted on the rigid plate with a width of 0.275 mm and a length of 2.4 m. The rigid plate slope can be changed by lifting one of its ends. There were five roughness elements installed in the downstream of the culvert.



a) Plan view



b) Longitudinal section view

**Figure 3. Staggered roughness elements used in the test (not in scale).**

**Figure 4. Experimental image of second phase.**

***Table 2. Dimensions of test roughness elements in phase 1.***

| Parameter | Symbols | Unit | Value |
|---|---|---|---|
| Hydraulic flume width | $B$ | mm | 73 |
| Roughness elements height | $h$ | mm | 10 |
| Gap width | $W_2$ | mm | 5 |
| | $W_1$ | mm | 21 |
| Roughness elements width | $W_3$ | mm | 19 |
| | $W_3/2$ | mm | 9.5 |
| Distance between roughness elements | $L$ | mm | 100 |

***Table 3. Dimensions of test roughness elements in phase 2.***

| Parameter | Symbols | Unit | Value | | | |
|---|---|---|---|---|---|---|
| Hydraulic flume width | $B$ | mm | 275 | 275 | 275 | 275 |
| Roughness elements height | $h$ | mm | 30 | 25 | 20 | 15 |
| Gap width | $W_2$ | mm | 15 | 12.5 | 10 | 7.5 |
| | $W_1$ | mm | 81.7 | 83.3 | 85.0 | 86.7 |
| Roughness elements width | $W_3$ | mm | 76.7 | 79.2 | 81.7 | 84.2 |
| | $W_3/2$ | mm | 38.3 | 39.6 | 40.8 | 42.1 |
| Distance of roughness elements | $L$ | mm | 255÷300 | 213÷250 | 170÷200 | 128÷150 |

### 2.2. Experimental scenarios of the physical models

The first physical model was conducted with the constant maximum discharge of 6.83 m$^3$/h (or 0.0019 m$^3$/s) with four culvert slopes of 2 %, 3 %, 4 % and 5 %, and two types of roughness elements with and without gaps. The first physical model included 36 scenarios in total.

The second physical model were performed with the discharge of 59.65 m$^3$/h (or 0.0166 m$^3$/s), five culvert slopes of 5 %, 7 %, 9 %, 11 % and 13 %, and four types of roughness elements with and without gaps. The second physical model included 36 scenarios in total as well.

### 2.3. Calculation other hydraulic parameters

The Froude number was used in this study. It is known that the dominant forces in open channel problems are controlled by gravity, viscosity and other effects can be neglected, and the Froude's model law is applied. It means that the ratio of gravitational forces to inertial forces is the same in both physical models and prototypes to maintain dynamic similarity. The following hydraulic parameters are required to assess the effect of the roughness elements in box culverts:

- average observed flow depth $(y)$ along the model was determined by N.D. Phong, H.T. Hai [22];
- the average velocity $(V)$ is calculated from the continuity equation;
- the Froude number is a dimensionless parameter measuring the ratio of “ratio of the flow inertia to the external field” the inertial force divided by gravitational force. The Froude number can be expressed as:

$$Fr = V/(gy)^{0.5}, \tag{1}$$

where, $Fr$ is the Froude number and $V$ is average velocity (m/s).

- water column velocity is defined as follows:

$$h_V(m) = V^2/(2g), \tag{2}$$

where, $g$ is the gravity acceleration (m/s$^2$).

- Specific energy

$$E_S(m) = y + h_V. \tag{3}$$

- Energy dissipation efficiency $\Delta E$ (%):

$$\Delta E = (E_{S1} - E_{S2})/E_{S1}.100\%, \tag{4}$$

where, $E_{S1}$ is the specific energy of a flow referred to the culvert bed without roughness elements; $E_{S2}$ is the specific energy of a flow referred to the culvert bottom with roughness elements.

## 3. Results and Discussion

### 3.1. Hydraulic features

Based on the results of monitoring flow rate and flow depth at measurement points we calculated average flow rate, flow kinetic energy, the Froude number, velocity ratio, flow kinetic energy ratio with and without roughness elements. The experimental results and calculation of the average velocity, the Froude number, kinetic energy and flow energy at the outlet of the hydraulic flume are given in Table 4.

The results show that average depth reduced with the increasing of slope in all cases. In case of the presence of roughness elements with gaps the average depth reduced less than without gaps. The average velocity is proportional to slope and roughness elements with and without gap, and flow is supercritical $(Fr > 1)$ at flow rate of 0.0019 m$^3$/s with four flat bottom flume slopes ranging from 2 % to 5 %. The Froude number and velocity head increase in all cases of testing and are smaller in case of the roughness elements without gaps. The specific energy increase in case of no roughness elements and a decrease in cases of roughness elements the without gaps; there is a slight reduction in case of roughness elements with gaps.

**Table 4. Experimental results and calculation of Froude number, kinetic energy and the flow**

***energy without roughness elements and with a different number of roughness elements.***

| Slope (%) | No roughness elements | Number of roughness elements without gap | | | | Number of roughness elements with gap | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 20 | 15 | 10 | 5 | 20 | 15 | 10 | 5 |
| Average depth $y$ (m) [20] | | | | | | | | | |
| 2 | 0.027 | 0.058 | 0.057 | 0.056 | 0.050 | 0.054 | 0.052 | 0.051 | 0.048 |
| 3 | 0.023 | 0.054 | 0.050 | 0.055 | 0.047 | 0.048 | 0.046 | 0.046 | 0.044 |
| 4 | 0.021 | 0.052 | 0.046 | 0.049 | 0.044 | 0.046 | 0.044 | 0.045 | 0.042 |
| 5 | 0.020 | 0.051 | 0.045 | 0.048 | 0.042 | 0.045 | 0.044 | 0.044 | 0.043 |
| Average velocity $V$ (m/s) | | | | | | | | | |
| 2 | 0.975 | 0.452 | 0.458 | 0.467 | 0.523 | 0.484 | 0.499 | 0.506 | 0.545 |
| 3 | 1.118 | 0.481 | 0.525 | 0.476 | 0.559 | 0.540 | 0.563 | 0.564 | 0.594 |
| 4 | 1.219 | 0.498 | 0.563 | 0.529 | 0.598 | 0.563 | 0.592 | 0.580 | 0.619 |
| 5 | 1.300 | 0.510 | 0.578 | 0.542 | 0.619 | 0.578 | 0.591 | 0.591 | 0.605 |
| Froude number $Fr$ | | | | | | | | | |
| 2 | 1.906 | 0.601 | 0.614 | 0.631 | 0.748 | 0.667 | 0.698 | 0.712 | 0.796 |
| 3 | 2.342 | 0.660 | 0.753 | 0.651 | 0.828 | 0.785 | 0.835 | 0.838 | 0.907 |
| 4 | 2.664 | 0.696 | 0.835 | 0.762 | 0.915 | 0.837 | 0.903 | 0.874 | 0.965 |
| 5 | 2.935 | 0.721 | 0.870 | 0.789 | 0.965 | 0.870 | 0.899 | 0.899 | 0.931 |
| Kinetic energy $h_\text{v}$ (m) | | | | | | | | | |
| 2 | 0.048 | 0.010 | 0.011 | 0.011 | 0.014 | 0.012 | 0.013 | 0.013 | 0.015 |
| 3 | 0.064 | 0.012 | 0.014 | 0.012 | 0.016 | 0.015 | 0.016 | 0.016 | 0.018 |
| 4 | 0.076 | 0.013 | 0.016 | 0.014 | 0.018 | 0.016 | 0.018 | 0.017 | 0.020 |
| 5 | 0.086 | 0.013 | 0.017 | 0.015 | 0.020 | 0.017 | 0.018 | 0.018 | 0.019 |
| Specific energy $E_\text{S}$ (m) | | | | | | | | | |
| 2 | 0.075 | 0.068 | 0.067 | 0.067 | 0.064 | 0.066 | 0.065 | 0.064 | 0.063 |
| 3 | 0.087 | 0.066 | 0.064 | 0.066 | 0.062 | 0.063 | 0.062 | 0.062 | 0.062 |
| 4 | 0.097 | 0.065 | 0.062 | 0.063 | 0.062 | 0.062 | 0.062 | 0.062 | 0.062 |
| 5 | 0.106 | 0.064 | 0.062 | 0.063 | 0.062 | 0.062 | 0.062 | 0.062 | 0.062 |

Calculation results of the reduction in flow energy with the presence of roughness elements are given in Table 5 and Figure 5, which show that the flow energy increases less with no gaps than with gaps and can be further reduced with more elements. The roughness elements with gaps show better energy reduction efficiency for slope culverts of 2 %, 3 %, however for the culverts on a larger slope of 4 %, 5 %, the energy reduction efficiency is almost the same.

***Table 5. Flow energy reduction with different numbers of roughness elements.***

| Slope (%) | Flow energy reduction $\Delta E$ (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Number of roughness elements without gaps (A) | | | | Number of roughness elements with gaps (B) | | | |
| | 20 | 15 | 10 | 5 | 20 | 15 | 10 | 5 |
| 2 | 9.6 | 10.2 | 11.1 | 15.2 | 12.6 | 13.7 | 14.2 | 16.3 |
| 3 | 24.3 | 26.9 | 24.0 | 28.2 | 27.6 | 28.3 | 28.4 | 29.0 |
| 4 | 33.2 | 35.8 | 34.7 | 36.4 | 35.8 | 36.3 | 36.1 | 36.6 |
| 5 | 39.5 | 41.6 | 40.7 | 42.0 | 41.6 | 41.8 | 41.8 | 41.9 |
| Mean | 26.6 | 28.6 | 27.6 | 30.5 | 29.4 | 30.1 | 30.1 | 31.0 |

*Table 6. Velocity reduction with different numbers of roughness elements.*

| | Percent velocity reduction (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Slope (%) | Number of roughness elements without gaps (A) | | | | Number of roughness elements with gaps (B) | | | |
| | 20 | 15 | 10 | 5 | 20 | 15 | 10 | 5 |
| 2 | 53.7 | 53.0 | 52.1 | 46.4 | 50.4 | 48.8 | 48.1 | 44.2 |
| 3 | 57.0 | 53.1 | 57.4 | 50.0 | 51.7 | 49.7 | 49.6 | 46.9 |
| 4 | 59.1 | 53.8 | 56.6 | 51.0 | 53.8 | 51.4 | 52.4 | 49.2 |
| 5 | 60.8 | 55.6 | 58.3 | 52.4 | 55.6 | 54.5 | 54.5 | 53.5 |
| Mean | 57.6 | 53.9 | 56.1 | 49.9 | 52.9 | 51.1 | 51.2 | 48.4 |

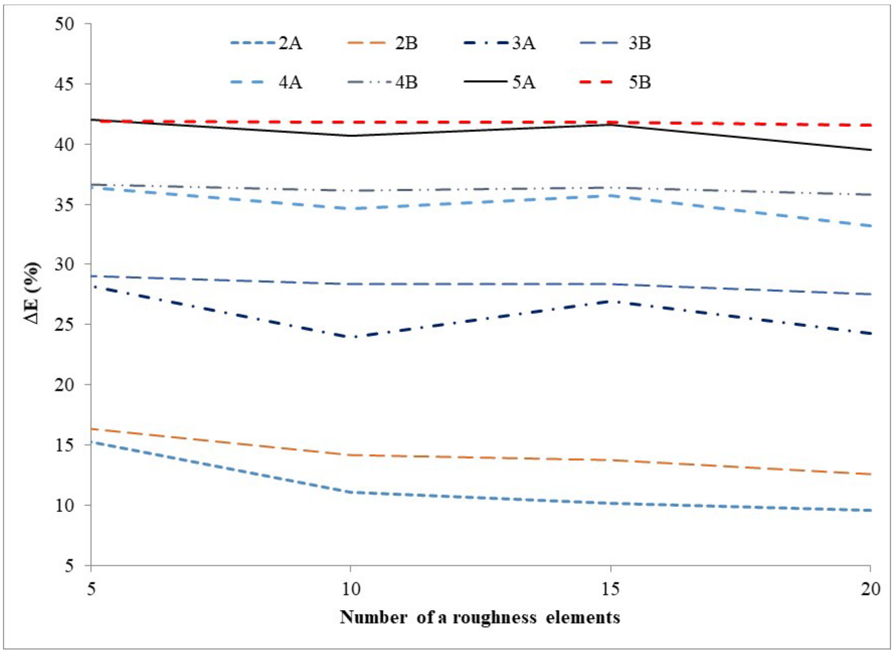


**Figure 5. Effect of different roughness elements number on the decrease of specific energy 2, 3, 4, 5 – slopes of test flume (A – roughness elements without gaps and B – roughness elements with gaps).**

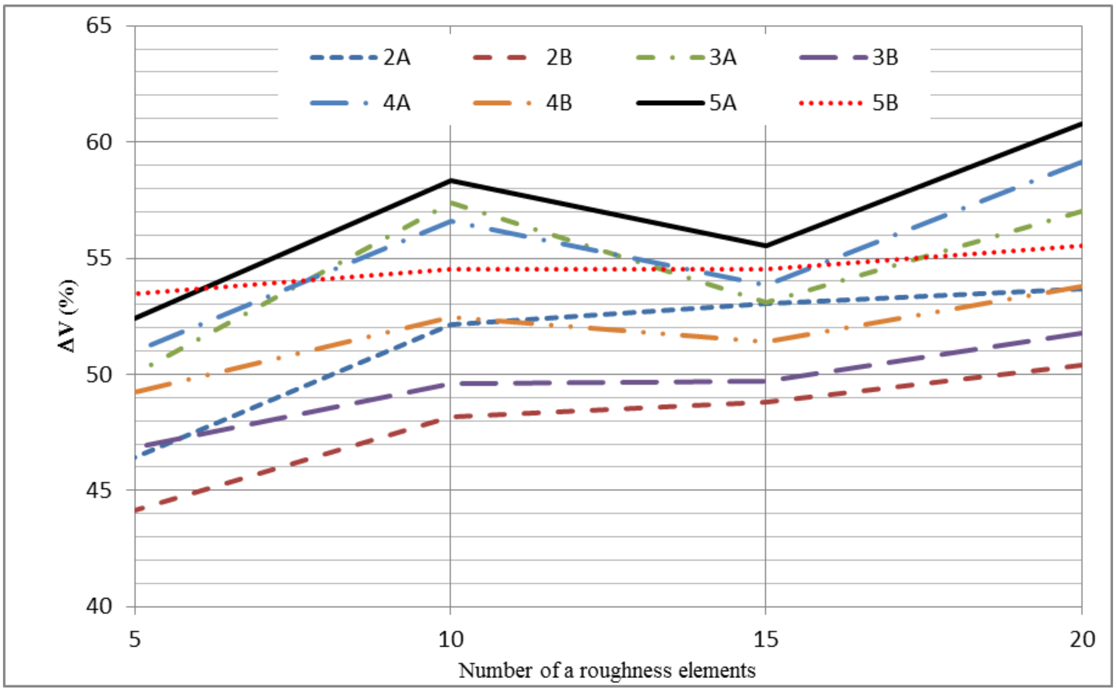


**Figure 6. Effect of different roughness elements number on the decrease of velocity 2, 3, 4, 5 – slopes of test flume (A – roughness elements without gaps and B – roughness elements with gaps).**

The flow energy in case of roughness elements present decreased compared to the case without a roughness element: the greater the slope, the greater the energy reduction. However, for the case of small slope (2 %), the energy reduction was not significant because of 16.3 % maximum reduction with five roughness elements with gaps. Thus, it can be seen that the roughness elements are suitable for slope culverts of 5 %; the energy reduction in this case is about 40 %.

In case of roughness elements without gaps, the velocity reduction decreased from 57.65 % to 39.93 % on average when the number of roughness elements decreased from 20 to 5, respectively. Similarly, in case of roughness elements with gaps, the velocity reduction decreased from 52.87 % to 48.43 % on average. These velocity reductions are larger than research results carried out by J. Wiggert, P. Erfle [23] (for the channel slope of 4.3 %, the average velocity reduction was 42.43 % and maximum 50.4 %).

The velocity reduction was proportional to the channel slope. For roughness elements with gaps, the velocity reduction increased from 44.14 % (for the number of roughness element of 5) to 55.56 % (for the number of roughness element of 20) on average when the channel slope rose from 2 % to 5 %, respectively. For roughness elements without gaps, the velocity reduction increased from 46.4 % (for the number of roughness element of 5) to 60.78 % (for the number of roughness element of 20) on average when the channel slope rose from 2% to 5 %.

In case of a larger number of roughness elements, the velocity decreased but the energy reduction efficiency almost remained the same and even decreases in some experiments. In general, it seemed that using more than five roughness elements at the end part of the culvert is disadvantageous as mentioned in P.L. Thompson, R.T. Kilgore [24].

From results of this research as well as previous researches on roughness elements, the row number of roughness elements arranged at the end of box culvert is recommended to be five. Five rows of roughness elements provide cyclical uniform flow pattern at the end of culvert, which maximizes the energy dissipation effect.

## *3.2. Affection of the roughness element heights*

The average velocity, the Froude number, kinetic energy and flow energy at the outlet of the test flume are given in Table 7, based on the results of the second physical model and calculation. The average depth decreased in all experiments. The heights of the roughness elements with gaps resulted in a smaller average depth than without roughness elements, and it is also smaller than the case where the roughness element has no gap.. The average velocity increased with the increasing of slope and without roughness elements. The average velocity, the Froude number, velocity head and specific energy increased with height of roughness elements higher than 30 mm and decreased in remaining heights.

***Table 7. Experimental results and calculation of the Froude number, kinetic energy and flow energy in case of no roughness elements and with roughness elements of different heights***

| Slope (%) | No roughness elements | Roughness elements height without gaps | | | | Roughness elements height with gaps | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 30 mm | 25 mm | 20 mm | 15 mm | 30 mm | 25 mm | 20 mm | 15 mm |
| | | | | Average depth $y$ (m) | | | | | |
| 5 | 0.039 | 0.103 | 0.092 | 0.089 | 0.069 | 0.103 | 0.087 | 0.083 | 0.071 |
| 7 | 0.030 | 0.108 | 0.093 | 0.084 | 0.069 | 0.081 | 0.086 | 0.079 | 0.068 |
| 9 | 0.028 | 0.103 | 0.101 | 0.084 | 0.081 | 0.088 | 0.091 | 0.072 | 0.061 |
| 11 | 0.026 | 0.101 | 0.112 | 0.097 | 0.081 | 0.076 | 0.103 | 0.102 | 0.079 |
| 13 | 0.026 | 0.098 | 0.106 | 0.104 | 0.110 | 0.076 | 0.097 | 0.089 | 0.085 |
| | | | | Average velocity $V$ (m/s) | | | | | |
| 5 | 1.532 | 0.572 | 0.643 | 0.665 | 0.864 | 0.577 | 0.677 | 0.713 | 0.829 |
| 7 | 2.006 | 0.548 | 0.638 | 0.707 | 0.858 | 0.731 | 0.686 | 0.751 | 0.865 |
| 9 | 2.086 | 0.575 | 0.584 | 0.707 | 0.728 | 0.671 | 0.652 | 0.826 | 0.970 |
| 11 | 2.309 | 0.586 | 0.527 | 0.608 | 0.728 | 0.781 | 0.575 | 0.580 | 0.745 |
| 13 | 2.276 | 0.605 | 0.561 | 0.568 | 0.538 | 0.783 | 0.612 | 0.663 | 0.693 |
| | | | | Froude number $Fr$ | | | | | |
| 5 | 2.489 | 0.568 | 0.677 | 0.712 | 1.054 | 0.575 | 0.731 | 0.790 | 0.990 |
| 7 | 3.729 | 0.532 | 0.669 | 0.780 | 1.042 | 0.820 | 0.746 | 0.854 | 1.056 |
| 9 | 3.953 | 0.572 | 0.586 | 0.780 | 0.815 | 0.721 | 0.691 | 0.986 | 1.254 |
| 11 | 4.606 | 0.589 | 0.502 | 0.622 | 0.815 | 0.905 | 0.572 | 0.580 | 0.844 |

| Slope (%) | No roughness elements | Roughness elements height without gaps | | | | Roughness elements height with gaps | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 30 mm | 25 mm | 20 mm | 15 mm | 30 mm | 25 mm | 20 mm | 15 mm |
| 13 | 4.507 | 0.618 | 0.551 | 0.561 | 0.518 | 0.909 | 0.628 | 0.709 | 0.758 |
| Kinetic energy $h_v$ (m) | | | | | | | | | |
| 5 | 0.120 | 0.017 | 0.021 | 0.023 | 0.038 | 0.017 | 0.023 | 0.026 | 0.035 |
| 7 | 0.205 | 0.015 | 0.021 | 0.025 | 0.037 | 0.027 | 0.024 | 0.029 | 0.038 |
| 9 | 0.222 | 0.017 | 0.017 | 0.025 | 0.027 | 0.023 | 0.022 | 0.035 | 0.048 |
| 11 | 0.272 | 0.017 | 0.014 | 0.019 | 0.027 | 0.031 | 0.017 | 0.017 | 0.028 |
| 13 | 0.264 | 0.019 | 0.016 | 0.016 | 0.015 | 0.031 | 0.019 | 0.022 | 0.025 |
| Specific energy $E_S$ (m) | | | | | | | | | |
| 5 | 0.158 | 0.120 | 0.113 | 0.112 | 0.107 | 0.120 | 0.111 | 0.109 | 0.106 |
| 7 | 0.235 | 0.123 | 0.113 | 0.109 | 0.106 | 0.108 | 0.110 | 0.108 | 0.107 |
| 9 | 0.250 | 0.120 | 0.119 | 0.109 | 0.108 | 0.111 | 0.112 | 0.106 | 0.109 |
| 11 | 0.297 | 0.118 | 0.126 | 0.116 | 0.108 | 0.107 | 0.120 | 0.119 | 0.108 |
| 13 | 0.290 | 0.116 | 0.122 | 0.121 | 0.125 | 0.107 | 0.116 | 0.112 | 0.110 |

Calculation results of the reduction in flow energy due to roughness elements are given in Table 8 and Figure 7.

The experimental results showed that the flow was supercritical $(Fr > 1)$ at the flow rate of 0.0166 m$^3$/s with different flume slopes in this study. Some experimental results of the roughness elements showed an area of 15 mm high $(h/B = 15/275 = 0.055)$ in supercritical flow $(Fr > 1)$. With the small roughness elements height $(h/B \leq 0.055)$, there seemed to be no advantage of energy dissipation efficiency, however, the effect of velocity reductions is relatively high.

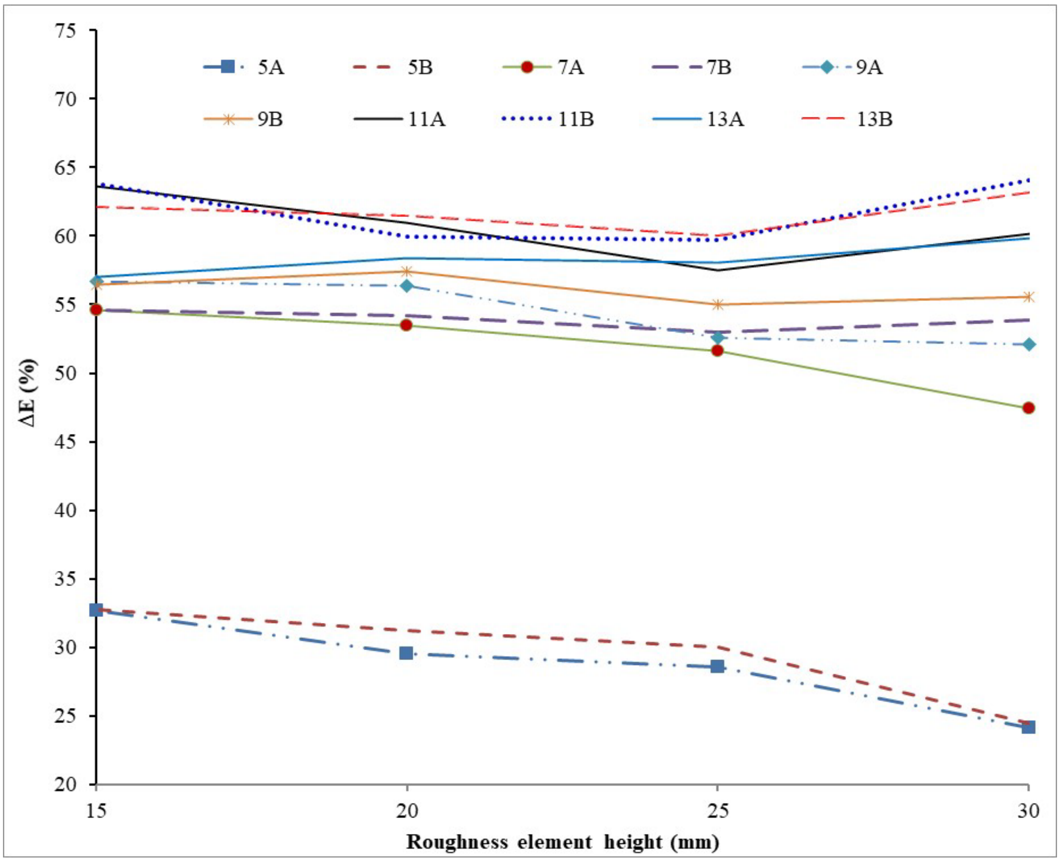


**Figure 7. Effect of different roughness elements height on the variation of the percent of specific energy. 5, 7, 9, 11, 13 – slopes of test flume (A – roughness elements without gaps and B – roughness elements with gaps).**

The energy dissipation efficiency was relatively small for a slope of 5 %, compared to the higher slopes (28.7 % with gapless roughness elements and 29.6 % with gap roughness elements). At the same time, there is a power dissipation efficiency of up to 50 % for slopes above 5 % (except dissipation efficiency of 47.4 % with the gapless roughness elements 30 mm high on a slope of 7 %). Similarly, the velocity reduction for the channel slope of 5 % is also relatively small compared to the case of steeper slopes.

The roughness elements with gaps gain a greater effective dissipation efficiency, averaging 58.4 % and 56.3 % compared with gapless abutments. The energy dissipation in models with roughness elements varied from $h/B = 20/275 = 0.073$ to $h/B = 30/275 = 0.109$ $\left(h/B \approx 0.1\right)$. The energy dissipation efficiency is almost unchanged: for example, in case of roughness elements with gaps on a slope of 11 %, the average power dissipation efficiency is 61.2 % while the smallest efficiency is 59.7 % and the maximum energy dissipation efficiency is 64.1 %. The energy dissipation efficiency in this study is equivalent to the research results carried by Nghi, Yen [25]. According to Nghi, Yen [25] the energy reduction in chute flow using roughness elements was average of 60.75 %, and maximum of 64 %.

Similar to the energy dissipation efficiency, the velocity reduction did not change much (from 67.2 % to 71.2 % for roughness elements without gaps and from 64.4 % to 67.7 % for roughness elements with gaps) in case of roughness elements heights from $h/B = 20/275 = 0.073$ to $h/B = 30/275 = 0.109$ $\left(h/B \approx 0.1\right)$. This velocity reduction is relatively consistent with the research on circular culverts using roughness elements carried by J.M. Wiggert and P.D. Erfle [12] (maximum velocity reduction of 68 % when $Fr = 7$).

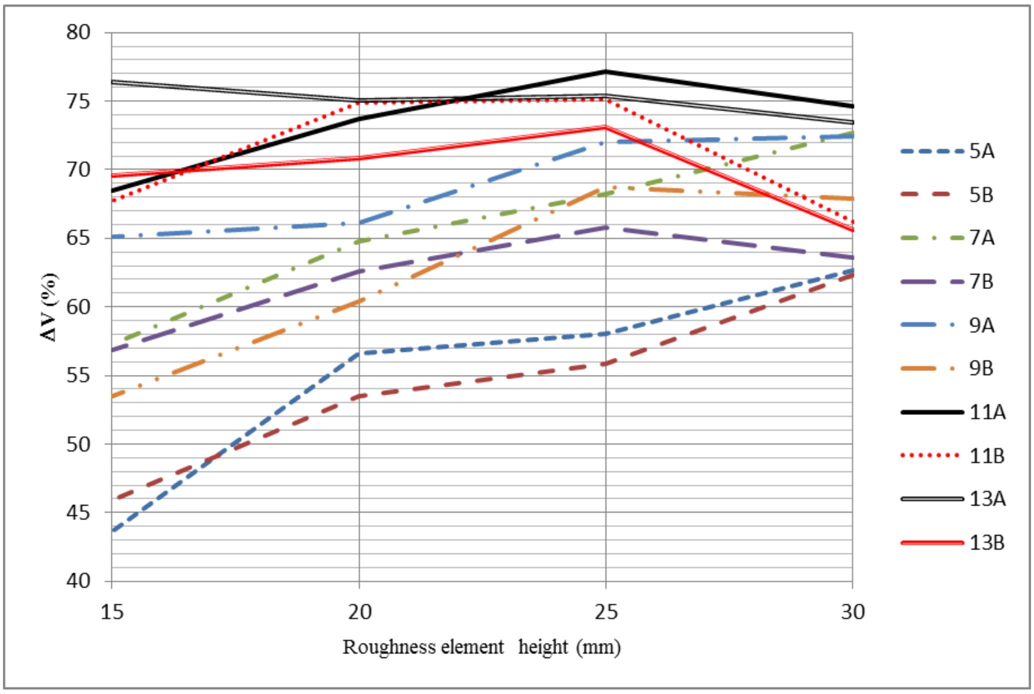


**Figure 8. Effect of different roughness elements height on the variation of the percent of velocity. 5, 7, 9, 11, 13 – slopes of test flume (A – roughness elements without gaps and B – roughness elements with gaps).**

***Table 8. Percent of flow energy reduction with the different heights of roughness elements.***

| Slope (%) | Reduction of specific energy (m) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Roughness elements height without gaps (A) | | | | Roughness elements height with gaps (B) | | | |
| | 30 mm | 25 mm | 20 mm | 15 mm | 30 mm | 25 mm | 20 mm | 15 mm |
| 5 | 24.1 | 28.5 | 29.5 | 32.7 | 24.5 | 30.0 | 31.2 | 32.8 |
| 7 | 47.4 | 51.6 | 53.5 | 54.6 | 53.9 | 53.0 | 54.2 | 54.6 |
| 9 | 52.1 | 52.5 | 56.3 | 56.7 | 55.5 | 55.0 | 57.4 | 56.4 |
| 11 | 60.2 | 57.5 | 60.9 | 63.6 | 64.1 | 59.7 | 59.9 | 63.8 |
| 13 | 59.8 | 58.1 | 58.4 | 57.0 | 63.2 | 60.1 | 61.5 | 62.1 |
| Mean | 48.7 | 49.7 | 51.7 | 52.9 | 52.2 | 51.6 | 52.8 | 53.9 |

***Table 9. Percent of velocity reduction with the different heights of roughness elements.***

| Slope (%) | Percent velocity reduction (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Roughness elements height without gap (A) | | | | Roughness elements height with gap (B) | | | |
| | 30 | 25 | 20 | 15 | 30 | 25 | 20 | 15 |
| 5 | 62.6 | 58.0 | 56.6 | 43.6 | 62.4 | 55.8 | 53.5 | 45.9 |
| 7 | 72.7 | 68.2 | 64.8 | 57.2 | 63.6 | 65.8 | 62.6 | 56.9 |
| 9 | 72.5 | 72.0 | 66.1 | 65.1 | 67.8 | 68.8 | 60.4 | 53.5 |
| 11 | 74.6 | 77.2 | 73.7 | 68.5 | 66.2 | 75.1 | 74.9 | 67.7 |
| 13 | 73.4 | 75.4 | 75.1 | 76.4 | 65.6 | 73.1 | 70.9 | 69.5 |
| Mean | 71.2 | 70.1 | 67.2 | 62.2 | 65.1 | 67.7 | 64.4 | 58.7 |

# 4. Conclusions

The impact of roughness elements on reducing flow velocity at outlets of box culverts considering the local characteristics of Vietnam was assessed in this study. Based on the experimental results, the following conclusions can be drawn:

1. The energy dissipation efficiency increases along with the increase in the number of roughness elements, but insignificantly. Therefore, five roughness elements are recommended to install at the end of the box culverts to ensure a relatively uniform cyclic flow pattern there.
2. Arrangement of roughness elements with staggered clearance at the end part of the sloping box culvert instead of gapless roughness elements provides greater energy dissipation efficiency; and at the same time, roughness elements with gaps contribute to passing of the sediment and reduce the deposition in drainage.
3. Roughness elements with gaps with a height of about 0.1 times the width of the culvert should be employed because with this height, the advantage of energy dissipation efficiency exceeds 50 %. If roughness elements height was small $\left(h/B < 0.055\right)$, there seemed to be no advantage of energy efficiency; if the roughness elements height was great, the power dissipation efficiency increased insignificantly, which causes more difficulties in construction and maintenance.
4. The results of this study are most suitable for box culverts with slopes from 5 % to 13%. When the culvert slope is larger, the same structure can be considered.

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