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# An Experimental Study of Roughness Elements to Design Fixed-Bed Hydraulic Model—A Step-by-Step Process and an Application in Vietnam

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**Abstract:** The calibration of the water level in a hydraulic model experiment is a time-consuming task. In this study, the authors proposed a guide to adjust the water level in the fixed-bed hydraulic experiment, by establishing a connection between the water level increase (ΔZ) in the model with other factors such as roughness diameter (d), roughness density (s), and flow velocity (v). Based on the results of 105 model experiments with different d, s, and v, the study also suggested a process to design a model experiment. The results of the study were used to build a fixed-bed hydraulic experiment for a river section passing through the Ialy hydropower plant in Vietnam. The results showed that after 01 time of implementation, the water level in the experiment was close to the observed water level. The differences between the calculated and measured water levels have been significantly reduced, from 0.027–0.036 m to 0.003–0.008 m. This finding shows that the approach of the study saves time and effort in the process of setting up a hydraulic experiment.

**Keywords:** flow velocity; hydraulic experiment; Ialy; roughness density; roughness diameter; water level

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## 1. Introduction

The operation of the flow is an extremely complex natural phenomenon, in which forces affect the flow, and how the flow develops has not been fully understood. To overcome these difficulties, the hydraulic model experiment has become an effective tool used by technicians [1,2]. In the process of building a hydraulic model, besides the required conditions related to the similarities of form, motion, and forces, the accurate simulation of water level in the real conditions is also of concern. Generally, the real conditions can be a channel or a river, and the data are usually just observed flood marks corresponding with particular discharge.

When the real condition is simulated, the roughness of the model is often unknow. This roughness value is usually estimated empirically or estimated based on formulas, such as the Manning equation [3], which the model was based on to get the expected roughness value. To ensure the accuracy of the model, the water level in the model was then compared with the actual measured value in the real condition. If the calculated results were not suitable with the observed data, the roughness value in the model would be adjusted. A common method to change the channel roughness is to attach grains, which are called roughness elements, to the flume. This is a trial-and-error task that requires a lot of time and effort. Therefore, it is necessary to have a specific process to help design such experiments more effectively.

Because of the importance of roughness in hydraulic models, many experiments have been conducted to determine roughness under different conditions. For instance, Giménez et al. (2001) [4] carried out 20 experiments to investigate the interaction between bed roughness and hydraulic flow in eroding rills. The study results showed that the increasing frequency of macroroughness variations and roughness amplitude with slope prevented an increase of flow velocity with slope. Nevertheless, the authors also indicated that the flow velocities depended on flow discharge, despite an increase of bed roughness with discharge. The study of Schlichting (1936) [5], which was based on the experimental results of Nikuradse (1933) [6], mentioned that the *ks* value was closely related to the grain diameter, in other words, the roughness diameter. The study results remain a good reference to this day. By 1984, Coleman et al. (1984) [7] improved the experiment in their study. Other studies suggested that the roughness density affected the roughness [8,9]. However, research which obtains the desired roughness in the model experiment are still limited. Therefore, it is necessary to give specific instructions when designing the physical model to reduce the effort of modeling.

From the above issues, this study focused on building database to evaluate the correlation between the water level change and different roughness diameters, roughness densities, and flow velocities. Based on such data, the study proposed a step-by-step process to design a hydraulic model. The results of the study were applied to a specific case to test the effectiveness of the approach.

## 2. Materials and Methods

The method of the study is presented in the below flow chart (Figure 1).

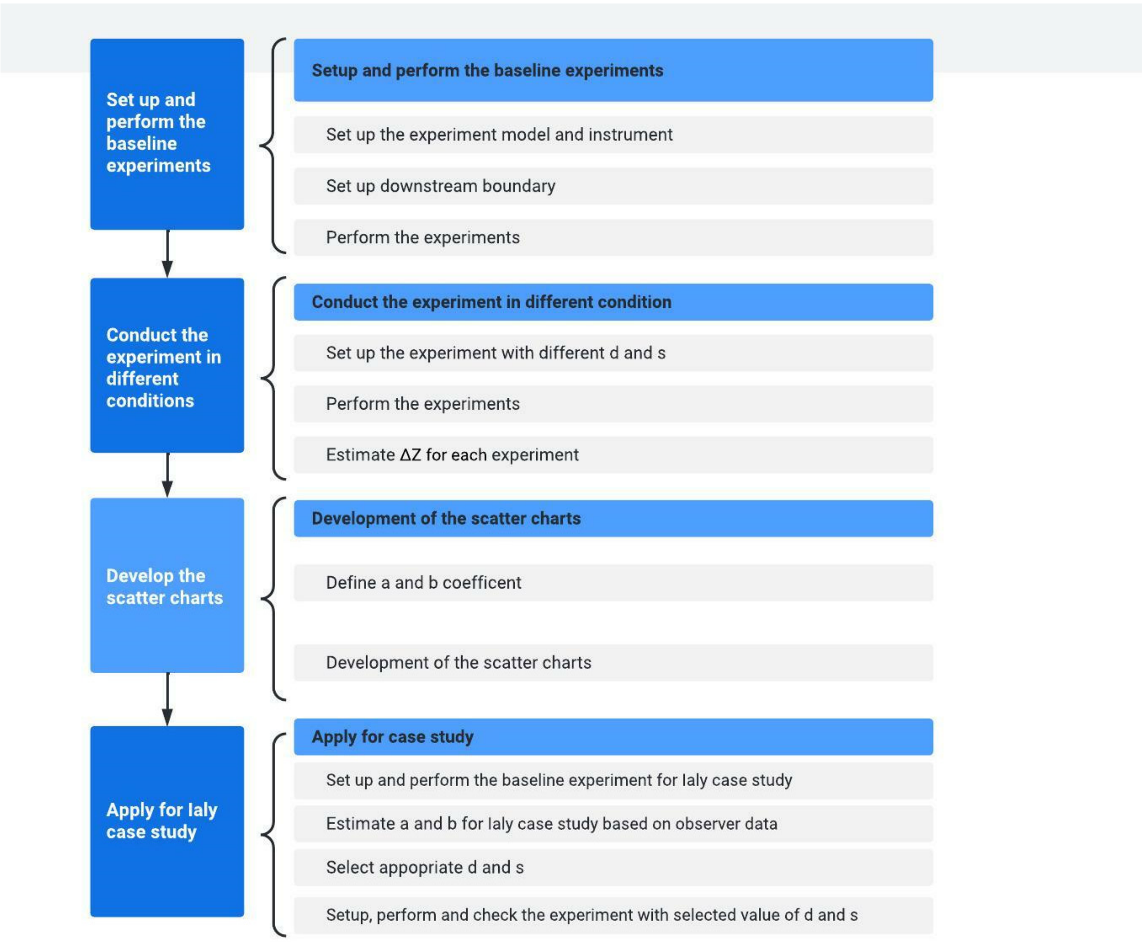
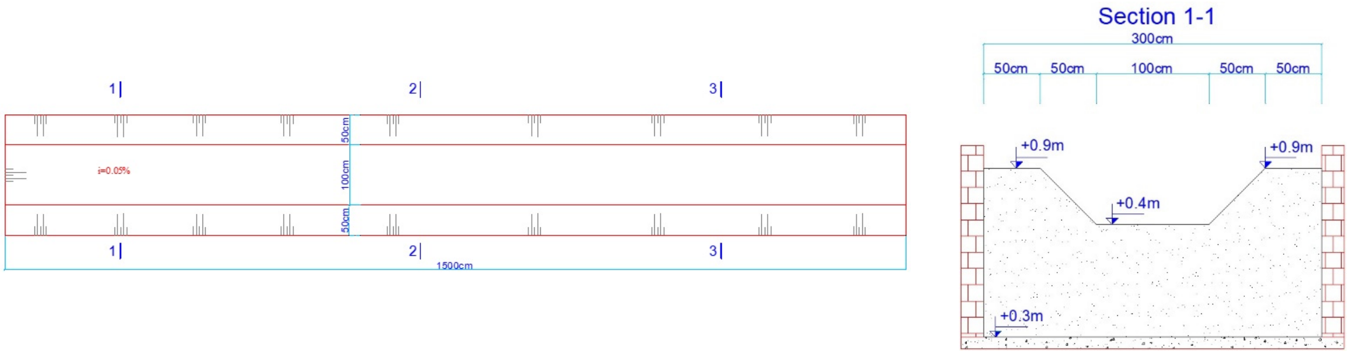



**Figure 1.** The methodology flow chart.

### 2.1. Experimental Installation and Measurements

The model was conducted at the laboratory of the Institute of Energy (Vietnam). The experiment flume was in the shape of a trapezoid, with 15 m long, 1 m bottom width, 1:1 sidewall slope, and 0.05% bottom slope. The surface of the flume was coated with sand cement at a ratio of 1:3 in 5 baseline experiments; in other experiments, roughness elements were added to the surface. The plain and cross-section views of the channel are shown in Figure 2.




(a) (b)

**Figure 2.** The geometry of experiment: (**a**) plain view; (**b**) cross section 1-1.

In all scenarios, the design discharge at the upstream was fixed at 90 L/s. To determine the discharge at the upper boundary in the experiments, a rectangular sharp weir was used. The flow through the weir can be calculated using the empirical Rehbock's Formula (1). The weir and gate flow theory can be found in many original works such as [10,11].

$$Q = C_d \frac{2}{3} \sqrt{2g} \cdot B \cdot H^{\frac{3}{2}} \quad \left(m^3/s\right) \tag{1}$$

where $C_d = 0.602 + 0.083H/P$

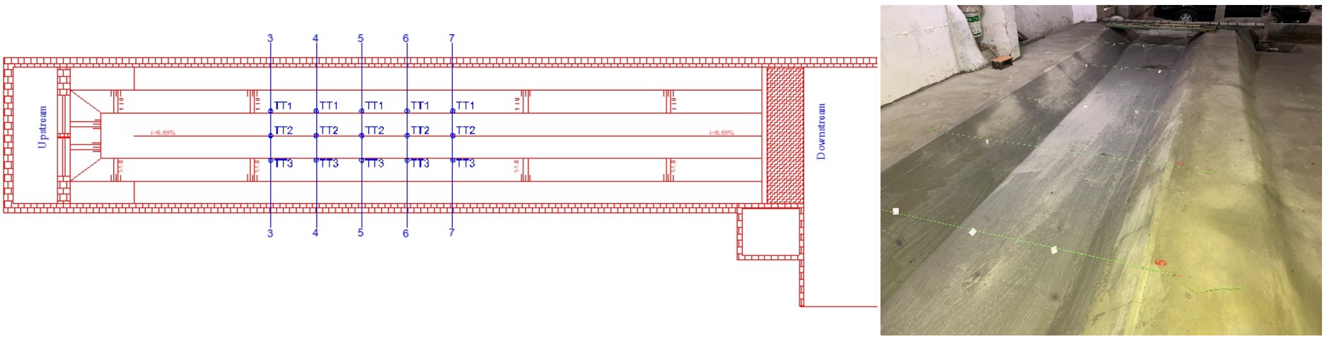
P is the height of weir (P = 3.2 m)

H is the head of water above the crest of the weir

B is the lateral width of the weir (B = 1.62575 m)

The controlled water levels at the downstream of the channel were 11.5 cm, 13.5 cm, 15.5 cm, 17.5 cm, and 19.5 cm. Corresponding to these values, the average flow velocity in the channel was divided into 5 levels as 0.71–0.8 m/s, 0.63–0.71 m/s, 0.50–0.63 m/s, 0.44–0.50 m/s, and <0.44 m/s. These scenarios were denoted as E_1_0_0, E_2_0_0, E_3_0_0, E_4_0_0, and E_5_0_0, respectively.

In each experiment, 15 measurement points were made at 5 cross-sections. The measurements at these 15 points were conducted by water level sensors with an error of <0.1 mm. The water level value at each cross-section was determined as the mean water level of the 3 measurement points on that cross-section. The locations to measure the water level are shown in Figure 3.

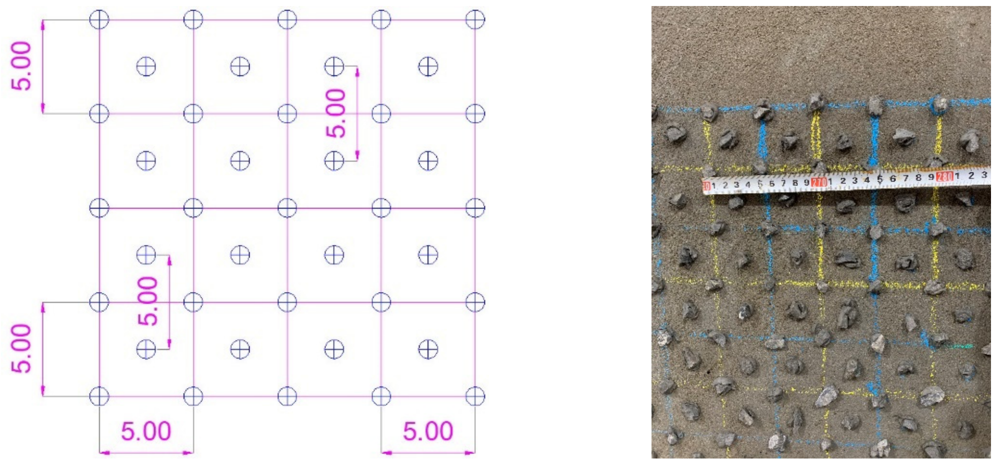



(**a**) (**b**)

**Figure 3.** The water level measurement locations: (**a**) design; (**b**) experiment setup.

*2.2. Attach the Roughness Elements to Increase Roughness*

In order to increase the roughness of the channel, the study attached roughness elements to the surface of the channel bottom and channel roof. The elements were attached at the corners and center of the squares with sides s were 2.5 d, 5 d, 7.5 d, 10 d, and 15 d, respectively. For each type of roughness elements with different diameters d, the densities among elements were different. Figure 4 shows how to attach the roughness elements with s = 5 d. Summary of the various arrangements of roughness elements is shown in Table 1.




(**a**) (**b**)

**Figure 4.** Attached roughness elements with d = 5–10 mm, s = 5 d: (**a**) design; (**b**) experiment setup.

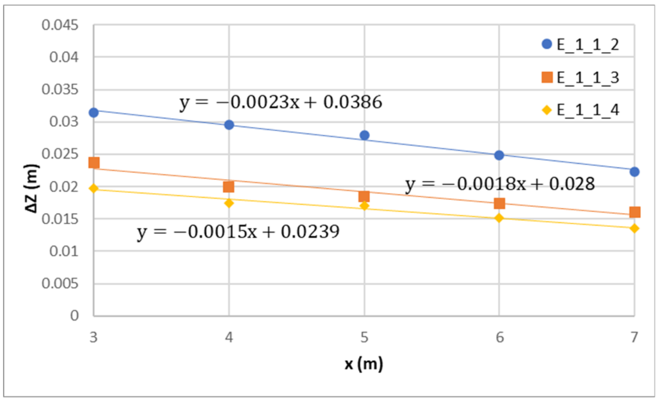
**Table 1.** Different scenarios for model design.

| d (mm) | s (mm) | | | | |
|---|---|---|---|---|---|
| 5–10 | 25 | 50 | 75 | 100 | 150 |
| 10–15 | 37.5 | 75 | 112.5 | 150 | 225 |
| 15–20 | 50 | 100 | 150 | 200 | 300 |
| 20–30 | 75 | 150 | 225 | 300 | 450 |

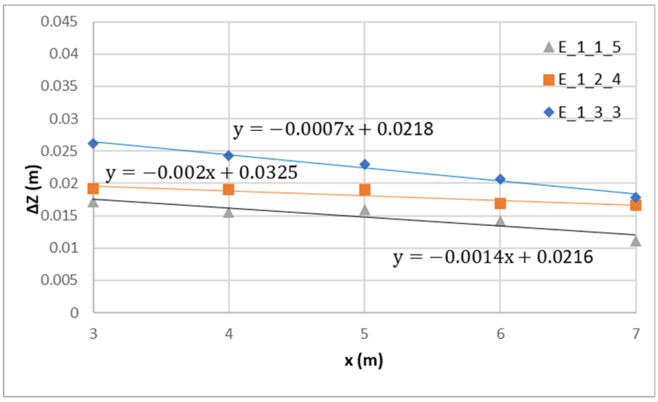
The study conducted 5 baseline experiments (without attaching roughness elements) corresponding with 5 different flow velocities. For each baseline experiment, the study in turn conducted simulations (attaching roughness elements) with 4 levels of roughness diameter d and 5 levels of distance s. These experiments were named in the format E_v_d_s, in which v was from 1 to 5 corresponding to 5 velocity levels of the scenarios described in Section 2.1, d from 1 to 4 corresponding to 4 levels of roughness diameter in Table 1, s from 1 to 5 corresponding to 5 levels of distance described in Section 2.2. For example, the experiment E_1_1_1 was performed with level 1 of velocity (v = 0.71–0.8 m/s), level 1 of roughness diameter (d = 5–10 mm), level 1 of distance (s = 2.5 d = 25 mm). The total number of experiments conducted was 105, including the 5 baseline experiments (without attaching roughness elements) and 100 experiments using roughness elements to simulate the roughness. In each roughness simulation experiment, the water level at each cross-section was compared with the respective baseline experiment (with the same flow velocity) to see the increase in the water level when the elements were attached.

### *2.3. Develop Process to Setup Experiment*

The results of the experiments showed that the differences in roughness diameters, densities among roughness elements, and flow velocities led to the increase of water level. Figure 5 describes the increases in water levels at cross-sections in several experiments when (a) attaching elements with the same diameters at different densities and when (b) attaching elements with different diameters at the same density. In general, the increases in water level decreased gradually from upstream to downstream in all experiments. This is shown by the slope of the linear regression lines connecting the 5 cross-sections in each experiment. However, this slope variable did not follow a specific rule.




(**a**)




(**b**)

**Figure 5.** The increase of water level at the cross-sections in experiments with: (**a**) same diameters & different densities; (**b**) different diameters & same densities.

In fact, a common problem was that the water level along the channel was not the same. This is very difficult when any change in roughness at any points would affect the water level of the whole channel. On the other hand, due to the differences of the channel lengths between the experimental condition (limited length) and the prototype (lengths can be longer or shorter), it is difficult to directly determine the degree of water level increase. To solve this difficulty, for each experiment, the study established a linear equation between the increase in water level $\Delta Z$ and the distance x from the upstream as (2).

$$\Delta Z = ax + b, \tag{2}$$

The study then built scatter charts showing the relationship between the coefficients a and b of the linear regression equations. These charts served as the basis for comparison to find the coefficient that matched the most with the observer data at cross-sections. Thus, instead of determining the degree of water level increase at each specific location, the study calibrated the water level of the whole channel via finding the most suitable linear regression line. By doing this, the study can ignore the length of the river section as well as preliminarily determine the appropriate degree of water level increase for all the flood marks.

### *2.4. Case Study*

The Ialy hydropower plant, located in the mainstream of Se San River in Ia Mo Nong Commune (Chu Pah District, Gia Lai Province) and Ya Tang commune (Sa Thay District, Kon Tum Province), has been put into operation since 2000. Waterflow is directed through the energy line to the plant located in Ya Tang Commune, Sa Thay District, Kon Tum Province. The study was applied to the river section at the downstream of the Ialy hydropower plant. The study river section is 2000 m long. The average width in the dry season is about 50 m; in the flood season, the width of the river bed increases to about 150 m. The average slope of the river bed is 1.32%. Figure 6 represents the river segment flow of the river section, in which the cross-sections TV0 and TV5 represent the beginning and the end of the studied river section. There are 3 locations to measure the actual water level, at the cross-sections, namely, TV1, TV2, and TV3. The water level at the cross-section TV4 is not used in the study considering the effects of the downstream on the value.

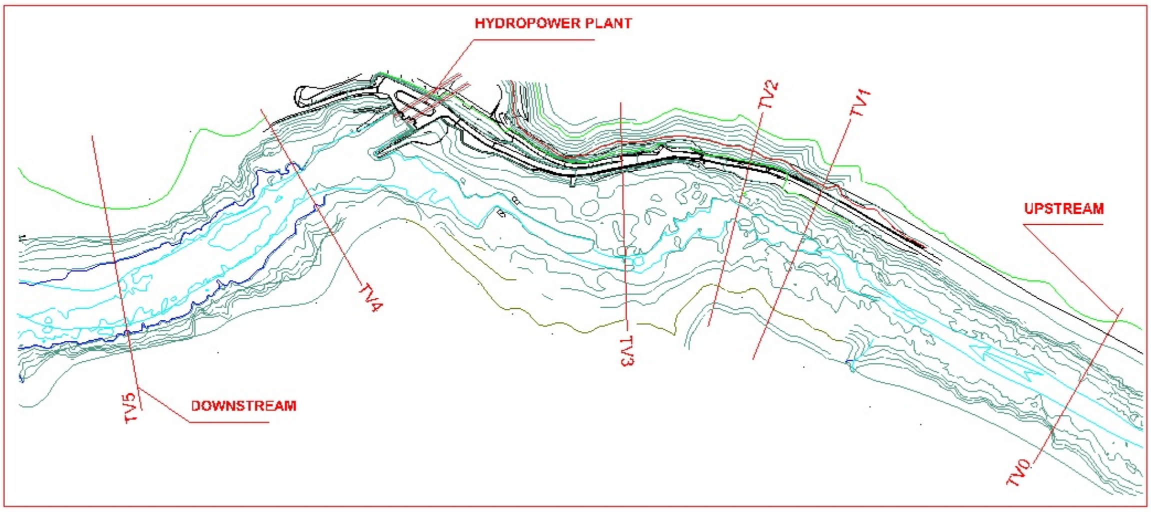



**Figure 6.** Plain view of river segment flow throught Ialy hydropower plant.

The study simulated the baseline experiment for the studied river section. Based on the results of the baseline experiment and the observed water level, the study designed roughness experiments for this river section. The results found the suitable roughness diameter and density for the experiment in the studied river section. The detailed results for the case study are discussed in the following section.

## 3. Results

### *3.1. Develop Process to Setup Experiment*

In order to meet the research goal which is to find an approach to reduce the effort when designing experiments, the study built five scatter charts of coefficients a and b corresponding with five levels of flow velocity as shown in Figure 7. Based on these charts, the process designing roughness for the experiments was carried out as follows. The first step was to establish a baseline model for the case study river section. Based on the results of the baseline experiment for the case study, the average flow velocity in the baseline experiment and the water level increase to be achieved at each location that had observed data were determined. Then, the coefficients a and b in the linear regression equation for the baseline experiment can be found for the case study. In the model testing, velocity also needs to be ensured with the same condition. Therefore, the next step in the process was to select the scatter chart in which velocity was appropriate to the velocity determined in the baseline experiment for the case study. Based on the water level from the baseline experiment for the case study and the flood marks, the study determined the needed water level increase in each cross-section in the baseline experiment, from which coefficients a and b were determined. These values of a and b were then projected on the scatter chart which was selected in the previous step. After that, the study selected which experiment (s) had the closest coefficients a and b. Looking back at the database, the study found out the needed roughness diameter and the needed density among the roughness elements to design the experiment.

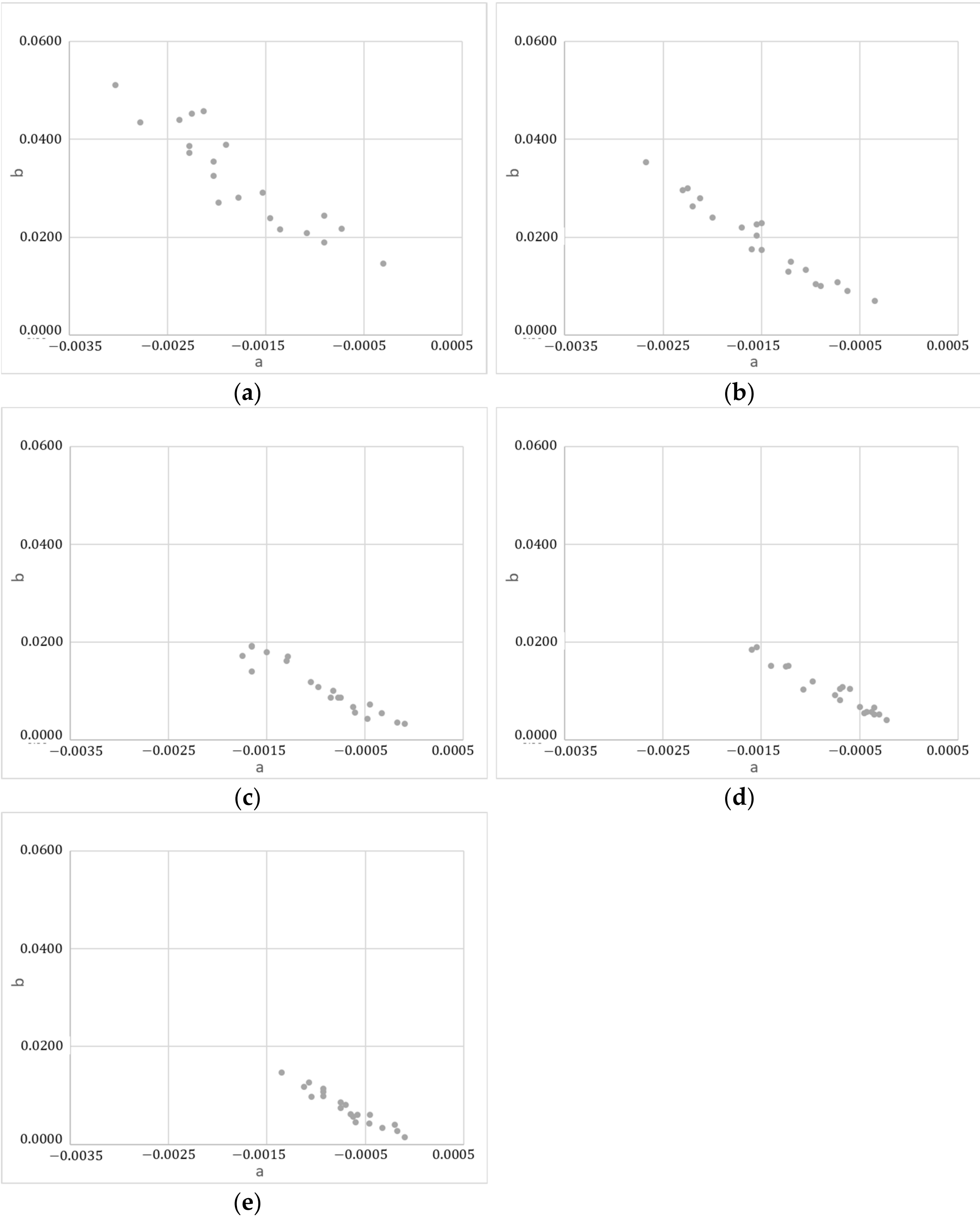



**Figure 7.** The 5 scatter charts of coefficients a and b corresponding with 5 levels of flow velocity: (**a**) v = 0.71–0.80 m/s; (**b**) v = 0.63–0.71 m/s; (**c**) v = 0.50–0.63 m/s; (**d**) v = 0.44–0.50 m/s; (**e**) v < 0.44 m/s.

## *3.2. Application for the River Segment through the Ialy Hydroelectric Plant*

### 3.2.1. Setup for Baseline Experiment

The experimental model was built at the model laboratory of the Energy Institute (Vietnam). The total model area was 200 $m^2$. The model was simulated in accordance with the actual river bathymetry, up to the elevation of 390 m. With such elevation, the river capacity would ensure the released flow. In the baseline experiment, this river section was simulated with a scale of 1/100. After the setup, the studied river section had the Q in the prototype at 11,000 $m^3/s$ (corresponding to the Q in the model at 110 L/s). The downstream of the model was determined as the observed water level at the cross-section TV5. The results of the water level in the baseline condition (bed river without roughness elements) for the case study are shown in the table below. Because the downstream of the model was at TV5, the water level was only calculated and compared at cross sections TV1, TV2, and TV3 in order to eliminate the effects of the boundary value (Table 2).

**Table 2.** The simulation results in baseline experiment and observer data.

| Cross Section | Distance (m) | Z Observed (m) | Z Baseline Experiment (m) | ΔZ (m) |
|---|---|---|---|---|
| TV1 | 4.078 | 3.315 | 3.279 | 0.036 |
| TV2 | 5.536 | 3.280 | 3.252 | 0.029 |
| TV3 | 7.392 | 3.248 | 3.222 | 0.027 |

### 3.2.2. Experiment Setup for Experiments with Roughness Elements Attached

Based on the velocity measured in the experiment, it was found that the velocity in the experiment was in level 1 with v > 0.71 m/s. Additionally, from the data in Table 2, the coefficients of the linear regression equation were determined as a = −0.00132 and b = 0.0363. The scatter chart of level 1 was selected and the coefficients a and b of the Ialy hydropower plant were updated as shown in Figure 8.

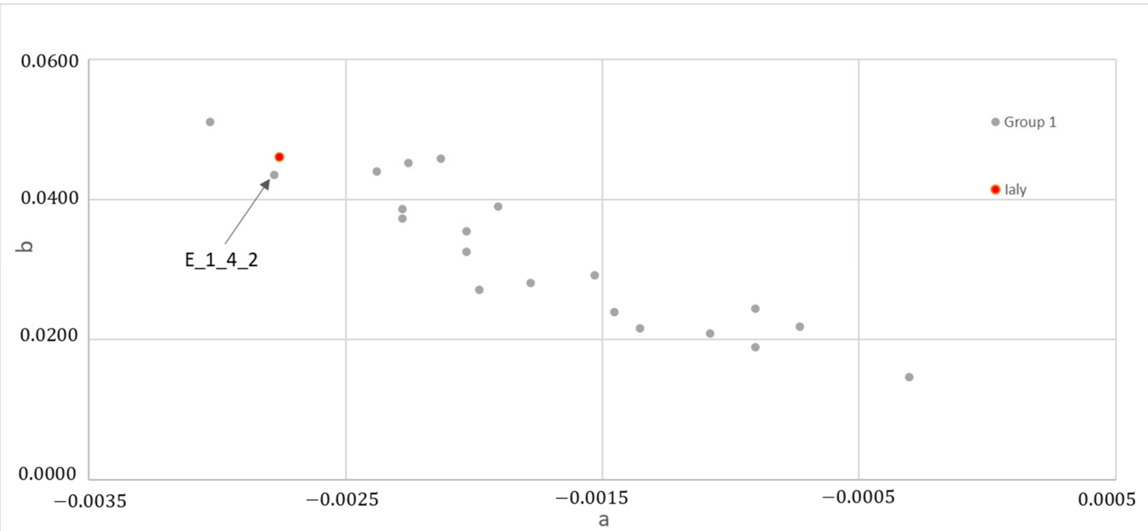



**Figure 8.** The coefficients plot of group 1 and Ialy hydropower plant.

Based on the chart, the closest point to the case study point was that in the experiment E_1_4_2 (−0.0028, 0.0435). From that result, the study selected the roughness diameter in level 4 (d = 20–30 mm) and the density in level 2 (s = 75 mm) to proceed with the model building. Figure 9 presents the baseline experiment and the experiment attaching grains.

(**a**) (**b**)

**Figure 9.** River section modeling in (**a**) baseline experiment, (**b**) attached grain experiment.

The water levels after attaching the roughness elements are presented in Table 3 below. It is noted that there are still differences between the simulated water level in the model and the actual measured water level. The maximum value at the cross-section TV2 was 0.008 m in the model, which was equivalent to 0.8 m in the prototype. This error is still large and will need to be refined by adding or removing beads near the cross-sections to make the simulated water level close to the measured values. This is a manual trial and the error process will not be discussed in detail in this study. It was found that after only 01 time of implementation, the simulated water level was close to the observed water level. This shows the effectiveness of this approach, in which the amount of effort to design the model was greatly reduced, which is exactly what the study aims to do.

**Table 3.** The simulation results in experiments that attached roughness elements and in observed data.

| Cross Section | Distance (m) | Z Observed (m) | Z Simulated (m) | ΔZ (m) |
|---|---|---|---|---|
| TV1 | 4.078 | 3.315 | 3.313 | 0.003 |
| TV2 | 5.536 | 3.280 | 3.272 | 0.008 |
| TV3 | 7.392 | 3.248 | 3.241 | 0.007 |

### *3.3. Limitation*

Although this approach shows great potential, some shortcomings remain. First, it should be emphasized that the range of velocity levels was limited. For future research, it is necessary to add experiments with higher flow velocities to increase the enrichment of the database. In addition, in some experiments, the data could be out of the proximity of points in the scatter charts, which makes it difficult to look up the roughness elements and the density to simulate the roughness in the experiment.

In this study, the level of uncertainty can come from the measurement of discharge and water level. These errors can be overcome by using high-precision measuring devices. However, the biggest source of error comes from the attachment of elements. As discussed, the elements used in the study are natural beads. This results in a very large variation in element sizes. In addition, attaching beads by cement depends a lot on the person who attached the beads. If not done well, the bonding part would increase the size of the elements. These are subjective errors that are difficult to avoid.

The choice of linear regression to determine the relationship between ΔZ and distance x is also a limitation, due to the uneven water level difference ΔZ along the channel. Water level calibration is a manual process that takes a lot of efforts. Furthermore, the number of observed locations and the river length in each certain case are different. To correctly calibrate the water levels in all measurement locations immediately is not feasible. Meanwhile, the goal of the study is to find the quickest way to make the simulated water level close to all of the observed data in general. Some errors are acceptable for now as this is only a preliminary design. Meanwhile, the design process should be simple.

Each selected design should define a certain diameter and a certain density of roughness elements. Therefore, the use of linear regression is the simplest solution as there is only one pair of coefficients (a and b).

## 4. Conclusions

The study conducted a number of experiments with different roughness diameters, roughness densities, and flow velocities. Based on the experiment results, the study created 05 scatter charts of the coefficients corresponding with 05 different flow velocity levels. Based on these charts, it is easy to find the roughness diameter and roughness density based on the observed data. The study was applied to the river section flowing through the Ialy hydropower plant in Vietnam. The results showed that the water level in the model was close to the observed water level. This helps reduce greatly the effort in the design process of the physical model.

**Author Contributions:** Conceptualization, C.K.T. and T.N.L.; methodology, C.K.T. and T.N.L.; formal analysis, C.K.T.; data curation, T.N.L., V.T. and T.D.H.; writing—original draft preparation, N.D.D., B.T.H.L. and T.N.L.; writing—review and editing, H.P.L. and H.C.V.; funding acquisition, H.C.V. All authors have read and agreed to the published version of the manuscript.

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