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Hydraulic Jump Investigation in Compound Channel with Irregular Roughness Arrangement Under Various Geometric and Hydraulic Conditions

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Abstract

Hydraulic jump, a rapidly changing flow phenomenon, has been encountered in many practical applications and refers to the transition of flow from supercritical to subcritical state. This research focuses on investigating hydraulic jumps in compound channel with irregular roughness arrangements under various geometric and hydraulic conditions using Flow-3D. The width and depth of the main channel are kept constant, while the width of the floodplains varies in three values: 18 cm, 22.5 cm, and 45 cm. Simulations are conducted for three depth ratios, three roughness height ratios, and three different velocities. The irregular roughness elements in the form of small blocks are embedded in the channel bed in a zigzag pattern. According to the simulation results, the presence of roughness elements led to a reduction in the secondary jump depth compared to the smooth case. For instance, with a floodplain width of 18 cm, a depth ratio of 0.3, a roughness height ratio of 2, and a velocity of 3.5 m/s, the average secondary depth decreased by approximately 5.64% compared to the smooth channel. However, with an increase in the floodplain width to 45 cm, the reduction in the secondary jump depth is about 12.59%. The minimum value of the secondary-to-initial jump depth ratio is observed at a relative depth of 0.6 and a roughness height ratio of 2. Furthermore, it is observed that the jump length significantly decreased with an increase in the roughness height ratios for smaller depth ratios. The jump length decreased by approximately 5.22% at the minimum value of the roughness height ratio, with a floodplain width of 18 cm, a velocity of 3.5 m/s, and a depth ratio of 3.0, and it decreases by approximately 29.97% at the maximum value of the roughness height ratio, with a velocity of 5 m/s and a depth ratio of 0.3. Additionally, increasing the floodplain width at a constant roughness height ratio resulted in a decreased in the jump length.

1. Introduction

Stilling basins are rarely used alone for complete control and restriction of hydraulic jumps due to the need for longer and higher walls, resulting in high construction costs. Therefore, measures should be taken to better control hydraulic jumps. One of these measures is the consideration of obstacles (blocks) at the beginning, middle, and end of the stilling basin used cubic-shaped roughness elements on the bed and installed them regularly in a rectangular channel with an area ratio of the elements to the total bed

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area equal to 10% (Mohammad Ali, 1991). He evaluated the length of the hydraulic jump as a function of the initial Froude number. The use of roughness elements on the channel bed improved the efficiency of the hydraulic jump, resulting in a reduction in secondary depth and roller length, stabilizing the jump location (Mohammad Ali, 1991). Carlo et al. (2007) studied natural rough beds consisting of sand with five different sizes, $0.46 < d_{50} < 3.2$, and within the range of Froude numbers 1.9 to 9.9, or relative roughness values $0 < \frac{K_s}{y_1} < 2.025$. They demonstrated that roughness elements caused a reduction in relative dual depths, roller lengths, and jump lengths (Novaes & Marques, 2024). Najandali et al. (2011) investigated the effect of triangular transverse roughness on the bottom of the pond on hydraulic jump characteristics with three roughness heights and four different distances between the roughnesses. Their results showed that energy loss increases by up to 18% compared to smooth bed (Najandali et al., 2011). Shafaie Bajestan and Nisi (2009) conducted research on hydraulic jumps on beds with cubic-shaped roughness elements with different arrangements, comparing the energy consumption of jumps on these beds with the energy consumption of jumps on smooth beds (Bajestan & Neisi, 2009) . In the same year, Shafaie Bajestan et al (2009) conducted another study on hydraulic jumps on beds with the same blocks, but with a lozenge-shaped layout (Bajestan & Neisi, 2009). Petruka (1958), Rajatnam (1968), Hager and Bormann (1989), and Chau (1959) referred to the simplest type of hydraulic jump formed in channels with rectangular cross-sections and horizontal beds as the classic hydraulic jump. An initial investigation by Rajaratnam (1968) showed that if the bed of the channel on which the jump is formed is rough, the jump length is significantly shorter than the jump formed on smooth beds. Further research by Hague and Flack (1984) and Hager (1992) confirmed the reduction in jump length and roller depth due to roughness (Vischer et al., 1998). The classic hydraulic jump has been extensively studied by (Rajaratnam, 1966). In his initial investigations on hydraulic jumps on rough beds, the dimensionless component k was defined based on the relationship (1), where k is dependent on the roughness height and the depth before the hydraulic jump.

$$k = \frac{k_e}{y_1} \tag{1}$$

Where k_e represents the equivalent roughness height and y_1 is the initial flow depth. Based on the initial Froude number and the value of k, the ratio of secondary depth to the initial depth can be calculated. The secondary depth of a hydraulic jump on a rough bed with a value of k approximately between 0.3 and 0.5 will decrease compared to the classical case (k equals zero). The length of roller and the length of jump also decrease close to half of the classical jump (Rajaratnam & Beltaos, 1977). According to Biryami (2011), when water exits from underground conduits, it has high velocity and destructive kinetic energy. Energy-consuming structures are employed to dissipate this destructive energy (Rajaratnam, 1968; Rajaratnam & Beltaos, 1977). According to Badiezadegan et al.'s research (2014), the relative length reduction compared to classical jumping is about 35% to 50%, and with the increase of the shear coefficient, it is 6.5 to 10 times smooth (Badiee Zadegan et al., 2014). Ghazali (2010), through 42 experiments conducted on triangular rough beds in the range of Froude numbers from 6.1 to 13.1 on a physical model of a tranquil basin, showed that the sequent depth and length of jump on triangular rough beds are 25% and 54.7% less, respectively, compared to smooth beds under the same hydraulic conditions (Ghazali, 2010). Bazaz and Ghorbani (2012), in a research on the effect of roughness wavelength on the characteristics of hydraulic jump, showed that the length of roughness reduces the length of the jump by 20% to 42% and the secondary depth of the jump by 10% to 18% (Bazaz et al., 2012). Parsamehr et al. (2012), investigated the characteristics of hydraulic jump on semi-cylindrical roughness in a channel with a width of 0.25 cm in the range of Froude number changes from 4.6 to 3.7 with three roughness heights to the radius (r). 1.5, 2.5, 3.5 cm and the distance (s), 1 to 4 times the diameter of the semi-cylinders. They stated that the maximum amount of secondary depth reduction on this type of beds is about 33.5% (Parsamehr et al., 2012). Parsamehr et al. (2016) conducted experiments in the range of Froude numbers from 3.4 to 12.4 in 3 densities and 4 rhombic discontinuous roughness arrangements and concluded that in the arrangement of 3 roughness combinations with 10.6 percent density The maximum decrease in secondary depth is 29.39% and the increase in energy consumption compared to the smooth bed is 10.94% on average (Parsamehr et al., 2016). Hassanzadeh Vayghan et al. (2019) investigated and tested the effect of placing a step in the outflow path of a horseshoe weir. The results obtained from these tests, in which two steps of 3.8 and 7.6 cm were used in the flow path, indicate an increase in the height of the secondary depth of the flow by a maximum of 272% and a decrease in the pressure on the pond bed. It is up to 45% (Hasanzadeh Vayghan et al., 2019). Javadi and Asadi (2021) investigated the effect of zigzag rectangular block geometry on hydraulic jump characteristics in a trapezoidal channel. The results obtained from these experiments showed that the average reduction in the ratio of conjugate depths in case of using rectangular blocks is 3.69% compared to the flat bed, and also, on average, using blocks The length of the hydraulic jump has decreased by 49.5% compared to the flat bed. The maximum flow energy loss on rectangular blocks is equal to 85.5% and its average increase compared to the smooth bed is equal to 46.3% (Javadi & Asadi, 2021). In the studies that have been done so far on hydraulic jump, jump in a simple rectangular channel with floor roughness has been investigated. Because the hydraulic jump in the compound channel was less studied and the compound channel has different hydraulic and geometric conditions in the main channel and floodplain sections, it is more similar to the channels in nature than other types of sections. A hydraulic jump was necessary in the composite channel. In this research, the aim was to investigate the hydraulic jump in the compound channel and the effect of floor roughness with irregular arrangement on the hydraulic jump.

2. Materials and Methods

This research focuses on investigating hydraulic jumps in a compound section with irregular bed roughness (zigzag pattern) using the Flow 3D software. The compound section is rectangular in shape and consists of a main channel and a floodplain section, with a total length of 12 m. Figure 2 shows the front view of the meshed composite channel. The depth and width of the main channel are kept constant. The simulations are performed for three different width ratios (w_r), four relative depths (D_r), and three roughness height ratios (n_r) defined as follows. Before carrying out the simulations, the relevant model was verified with the numerical model of the numerical simulation article of hydraulic jump in the composite channel (Alavi Moghadam et al., 2015). The input data for the software includes the initial flow velocity and depth. A velocity of 5 m/s and Five entry depths of 0.03, 0.04, 0.05, 0.06, and 0.07 m were used, along with the RNG turbulence model. Figure (1) illustrates the ratio of the secondary depth to the initial jump depth obtained from the validation results. It can be observed from this figure that the Flow 3D software demonstrates high accuracy in simulating hydraulic jumps (Talebi et al., 2025).

$$w_r = \frac{2b}{B} = 1.2 \text{ ، } 1.5 \text{ ، } 3 \qquad (2)$$

$$D_r = \frac{f}{H} = 0.3 \text{ ، } 0.4 \text{ ، } 0.6 \qquad (3)$$

$$n_r = \frac{\beta}{\alpha} = 2 \text{ ، } 3 \text{ ، } 5 \qquad (4)$$

Above, b is the width of the floodplain and B is the width of the main channel. f and H are the water depth in the floodplain and the water depth in the whole channel, respectively. β and α are roughness height in floodplain and main channel, respectively.

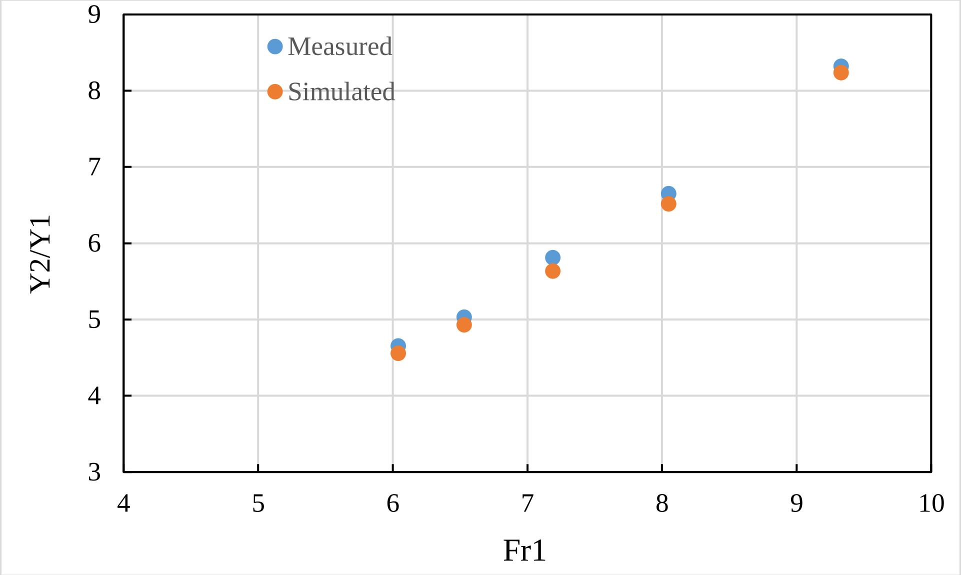

Figure 1. Comparison between measured and simulated the ratio of the secondary depth to the initial jump depth (Y2/Y1) at different Froude number (Fr1)

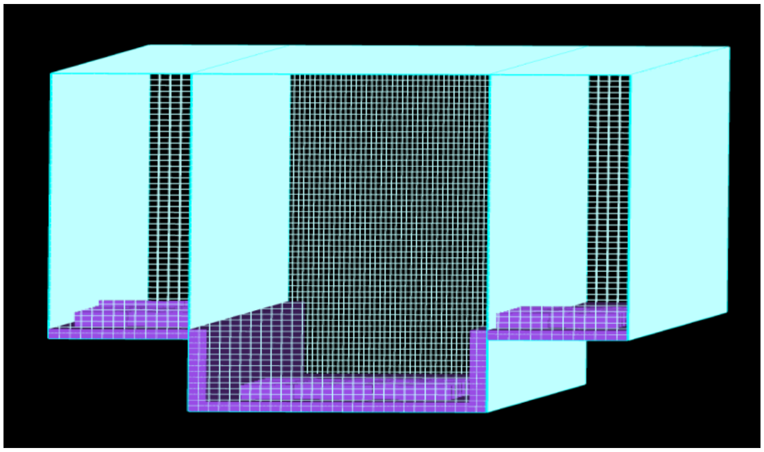

Figure 2. Front view of meshed composite channel with rough floor in Flow 3D

All simulations are performed at three different velocities. The bed roughness elements are in the form of small cubes, spaced 1 m apart from the beginning of the channel. The depth and width of the bed roughness elements in the main channel and floodplain sections are 6 cm. The height of the bed roughness elements in the main channel is set to 3 cm, while the height of the floodplain bed roughness elements varies at ratios of 3, 6, and 9 cm. The distance between each bed roughness element in the main channel is 3 cm and the distance between each bed roughness element in the floodplain sections is 2 cm. The distance between each group of bed roughness elements is 0.15

meters. Table 1 presents the geometric and hydraulic specifications of the compound channel. In the table, b_m and y_m represent the width and depth of the main channel, respectively, while b_f and y_f represent the width and depth of the floodplain.

Table 1. Geometric and hydraulic specifications of the compound channel

Roughness height ratio (n_r)	Relative depth (D_r)	Velocity V	b_m (cm)	y_m (cm)	b_f (cm)	y_f (cm)
2	0.3, 0.4, 0.6	3.5, 4.25, 5	15	30	18	6.4, 10, 22.5
3	0.3, 0.4, 0.6	3.5, 4.25, 5			22.5	6.4, 10, 22.5
5	0.3, 0.4, 0.6	4.5, 5.25, 6			45	6.4, 10, 22.5

Boundary conditions were applied to all six faces of the cube grid. The boundary conditions used in the simulation are as follows: the upper boundary is because in the simulations the velocity was applied as the value of the flow velocity, the lower boundary where the flow leaves the end of the channel as an outlet flow, the side wall boundary (y_{min}) is treated as a solid wall (right floodplain), the side wall boundary (y_{max}) is also treated as a solid wall (left floodplain), the lateral boundaries of the main channel are set as symmetric boundaries, and the bed boundaries of both the main channel and floodplains are treated as solid walls because the bottom of the channel is rigid. The water surface boundary is set as a symmetric boundary. Figure (3) illustrates the boundary conditions used in the numerical model.

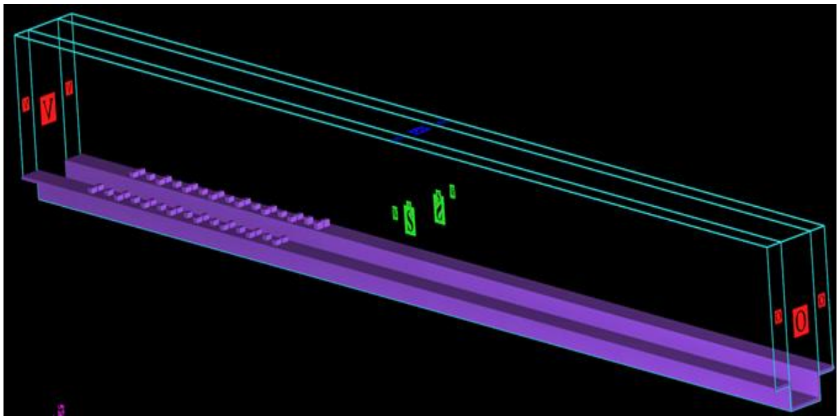

Figure 3. Illustrations of the boundary conditions used in the study.

3. Results and Discussion

Considering the main objectives of the research, this section analyzes the influence of rough bed with irregular arrangement on hydraulic jump characteristics in a compound channel, including the ratio of secondary to primary jump depths and the jump length.

3.1. Ratio of Secondary to Primary Jump Depths

This section investigates the ratio of secondary (Y_2) to primary (Y_1) jump depths in relation to the Froude number Fr_1, at a constant width ratio (w_r) and varying roughness height ratio (n_r) in a channel with irregular roughness arrangement. Figure (4) illustrates the ratio of secondary to primary jump depths $\frac{Y_2}{Y_1}$ with respect to the Froude number (Fr_1) at a width ratio of 1.2.

At a relative depth of 0.3, with a roughness height ratio of 2 and Froud number 2.61, the ratio of secondary to primary jump depths is approximately 5.64%. For a roughness height ratio of 3, the ratio decreases to around 7%, and for the maximum roughness height ratio of 5, the ratio decreases to approximately 9.73% compared to the channel without roughness. Furthermore, with an increase in Froud number 3.72, the ratio of secondary to primary jump depths decreases about 7.34% for a roughness height ratio of 2, 9.91% for a roughness height ratio of 3, and 12.09% for a roughness height ratio of 5 compared to the case of a smooth channel. At a relative depth of 0.4, with a roughness height ratio of 2 and a Froud number 2.38, the ratio of secondary to primary jump depths is approximately 4.12%. For a roughness height ratio of 3, the ratio decreases to around 5.53%, and for the maximum roughness height ratio of 5, the ratio decreases to approximately 7.44% compared to the channel without roughness. With an increase in Froud number 3.4, the ratio of secondary to primary jump depths decreases about 5.83% for a roughness height ratio of 2, 8.33% for a roughness height ratio of 3, and 11.27% for a roughness height ratio of 5 compared to the case of a smooth channel. At a relative depth of 0.6, with a roughness height ratio of 2 and Froud number 2.45, the ratio of secondary to primary jump depths is approximately 4.07%. For a roughness height ratio of 3, the ratio decreases to around 5.74%, and for the maximum roughness height ratio of 5, the ratio decreases to approximately 7.44% compared to the channel without roughness. With an increase in Froud number 3.26, the ratio of secondary to primary jump depths decreases to about 7.51% for a roughness height ratio of 2, 12.11% for a roughness height ratio of 3, and 17.58% for a roughness height ratio of 5 compared to the case of a smooth channel.

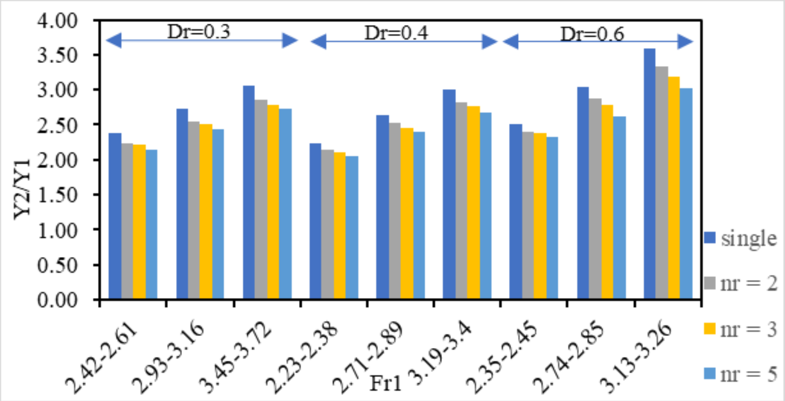

Figure 4. The ratio of ($\frac{Y_2}{Y_1}$) to the Froude number (Fr_1) for a width ratio of 1.2 (with a floodplain width of 18 cm) relative to the smooth channel.

Figure 5 illustrates the ratio of secondary to primary jump depths ($\frac{Y_2}{Y_1}$) with respect to the Froude number (Fr_1) for a width ratio of 1.5, relative to the smooth channel. At a relative depth of 0.3, with a roughness height ratio of 2 and Froud number 2.61, the ratio of secondary to primary jump depths is approximately 7.17%. For a roughness height ratio of 3, the ratio decreases to around 9.61%, and for the maximum roughness height ratio of 5, the ratio decreases to approximately 13.52% compared to the smooth channel case. Additionally, at an increased Froud number 3.72, the ratio of secondary to primary jump depths decreases to about 10.79% for a roughness height ratio of 2, 14.26% for a roughness height ratio of 3, and 17.84% for a roughness height ratio of 5, compared to the smooth channel case. At a relative depth of 0.4, with a roughness height ratio of 2 and Froud number 2.38, the ratio of secondary to primary jump depths is approximately 6.64%. For a roughness height ratio of 3, the ratio decreases to around 8.61%, and for the maximum roughness height ratio of 5, the ratio decreases to approximately 12.16% compared to the smooth channel case. With an increase in Froud number 3.4, the ratio of secondary to primary jump depths decreases to about 9.70% for a roughness height ratio of 2, 13.19% for a roughness height ratio of 3, and 16.60% for a roughness height ratio of 5, compared to the smooth channel case. At a relative depth of 0.6, with a roughness height ratio of 2 and Froud number 2.45, the ratio of secondary to primary jump depths is approximately 5.45%. For a roughness height ratio of 3, the ratio decreases to around 8.51%, and for the maximum roughness height ratio of 5, the ratio decreases to approximately 11.21% compared to the smooth channel case. With an increase Froud number 3.26, the ratio of secondary to primary jump depths decreases to about 10.37% for a roughness height ratio of 2, 15.63% for a roughness height ratio of 3, and 21.69% for a roughness height ratio of 5, compared to the smooth channel case.

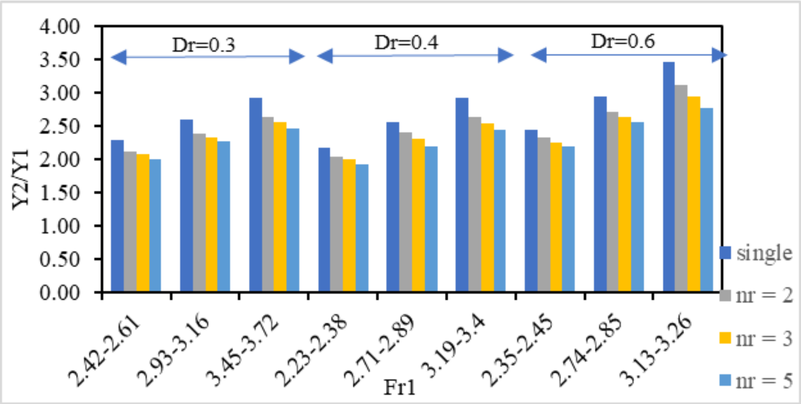

Figure 5. The ratio of ($\frac{Y_2}{Y_1}$) to the Froude number (Fr$_1$) for a width ratio of 1.5 (with a floodplain width of 22.5 cm) relative to the smooth channel.

In Figure 6, the ratio of secondary to primary jump depth ($\frac{Y_2}{Y_1}$) relative to the Froude number (Fr$_1$) at a width ratio of 3 is depicted. At a relative depth of 0.3, a height ratio of 2, and Froud number 2.61, the ratio of secondary to primary jump depth is approximately 12.59%. At a height ratio of 3, the ratio is about 15.31%, and at the maximum height ratio of 5, the ratio decreases to about 20.37% compared to the smooth channel. Additionally, with an increase in Froud number 2.72, the ratio of secondary to primary jump depth decreases to approximately 16.57% at a height ratio of 2, about 21.03% at a height ratio of 3, and around 25.21% at a height ratio of 5 compared to a smooth channel. At a relative depth of 0.4, a height ratio of 2, and Froud number 2.38, the ratio of secondary to primary jump depth is approximately 10.53%. At a height ratio of 3, the ratio is about 13.33%, and in the maximum case with a height ratio of 5, the ratio decreases to approximately 17.39% compared to the smooth channel. With an increase in Froud number 3.4, the ratio of secondary to primary jump depth decreases to approximately 14.31% at a height ratio of 2, about 18.79% at a height ratio of 3, and around 22.96% at a height ratio of 5 compared to a smooth channel. At a relative depth of 0.6, a height ratio of 2, and Froud number 2.45, the ratio of secondary to primary jump depth is approximately 8.11%. At a height ratio of 3, the ratio is about 12.41%, and in the maximum case with a height ratio of 5, the ratio decreases to approximately 16.39% compared to the smooth channel. With an increase in Froud number 3.26, the ratio of secondary to primary jump depth decreases to approximately 14.52% at a height ratio of 2, about 20.71% at a height ratio of 3, and around 27.91% at a height ratio of 5 compared to a smooth channel.

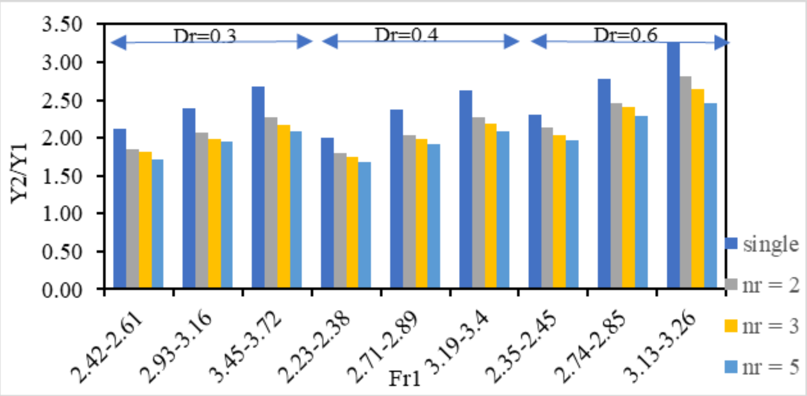

Figure 6. The ratio of ($\frac{Y_2}{Y_1}$) to the Froude number (Fr_1) for a width ratio of 3 (with a floodplain width of 45 cm) relative to the smooth channel.

As it is clear from the examination of figures 4 to 6, the increase in the ratio of the height of roughness (n_r) causes a decrease in the ratio of the secondary depth to the primary jump ($\frac{Y_2}{Y_1}$), also with the increase of the relative depth (D_r) in a ratio of the height of roughness (n_r) constant ratio of secondary depth to primary jump ($\frac{Y_2}{Y_1}$) decreases. In a constant relative depth and constant roughness height ratio, the increase in speed causes an increase in the secondary jump depth ratio. By looking at the graphs, we found that the increase in the ratio of the height of the roughness (n_r) causes a decrease in the ratio of the secondary to the primary depth of the jump ($\frac{Y_2}{Y_1}$) compared to the channel without roughness, but by comparing the ratio of the height of the roughness (n_r) to each other We concluded that increasing the ratio of the height of the roughness (n_r) does not have much effect on the ratio of the secondary depth to the primary jump ($\frac{Y_2}{Y_1}$). It was also found that the minimum change in the secondary to primary jump depth ratio ($\frac{Y_2}{Y_1}$) occurs in the roughness height ratio of 2. According to the comparison of the figures, it is generally observed that the increase in the width ratio in channels with uneven bed leads to a decrease in the secondary to primary depth ratio. Furthermore, as the relative depth increases at a constant rate, the ratio of secondary to primary depth decreases.

In Figure 7, in a channel with a rough bed at a relative depth of 0.3 and a constant Froud number 2.61, increasing the width ratio from 1.2 to 1.5 results in approximately a 5.74% reduction in the secondary-to-primary depth ratio. Furthermore, with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 13.07%. With an increase in Froud number 3.72, increasing the width ratio from 1.2 to 1.5 leads to a reduction of approximately 8.10% in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 15.07%.In a channel with a rough bed at a relative depth of 0.4 and a constant Froud number 2.38, increasing the width ratio from 1.2 to 1.5 results in approximately a 4.78% reduction in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 12.30%. With an increase in Froud number 3.4, increasing the width ratio from 1.2 to 1.5 leads to a reduction of approximately 7.10% in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 14.23%.In a channel with a rough bed at a relative depth of 0.6 and a constant Froud number 2.45, increasing the width ratio from 1.2 to 1.5 results in approximately a 4% reduction in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 8.54%. With an increase in Froud number 3.26, increasing the width ratio from 1.2 to 1.5 leads to a reduction of approximately 6.83% in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 10.14%.

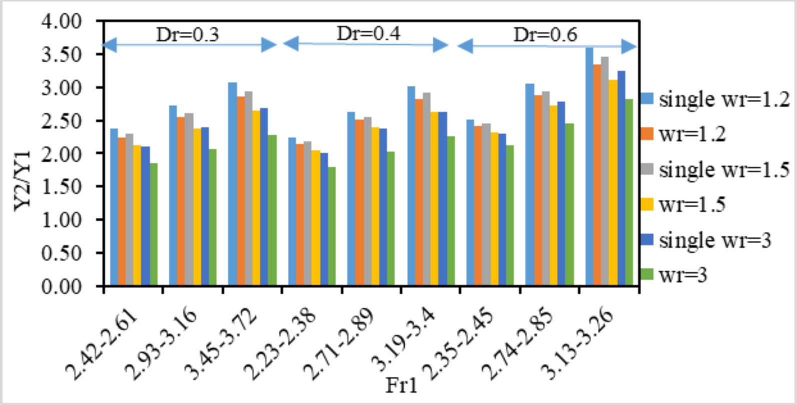

Figure 7. Illustrations the ratio of ($\frac{Y_2}{Y_1}$) to the Froude number (Fr_1) for a relative roughness height of 2 compared to a smooth channel.

As shown in Figure 8, in a channel with a rough bed at a relative depth of 0.3 and a constant Froud number 2.61, increasing the width ratio from 1.2 to 1.5 results in approximately a 6.20% reduction in the secondary-to-primary depth ratio. Furthermore, with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 14.16%. With an increase in Froud number 3.72, increasing the width ratio from 1.2 to 1.5 leads to a reduction of approximately 9.02% in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 16.02%. In a channel with a rough bed at a relative depth of 0.4 and a constant Froud number 2.38, increasing the width ratio from 1.2 to 1.5 results in approximately a 5.35% reduction in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 13.30%. With an increase in Froud number 3.4, increasing the width ratio from 1.2 to 1.5 leads to a reduction of approximately 7.94% in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 15.25%.In a channel with a rough bed at a relative depth of 0.6 and a constant Froud number 2.45, increasing the width ratio from 1.2 to 1.5 results in approximately a 5.19% reduction in the secondary-to-primary depth ratio, and with an increase in the width ratio from 5/1 to 3, the secondary-to-primary depth ratio decreases by approximately 9.79%. With an increase in Froud number 3.26, increasing the width ratio from 1.2 to 1.5 leads to a reduction of approximately 7.76% in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 11.09%.

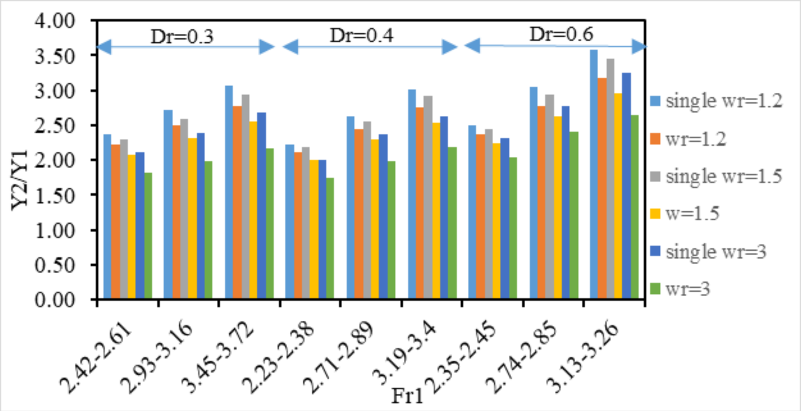

Figure 8. Illustrations of the ratio of $(\frac{Y_2}{Y_1})$ to the Froude number (Fr_1) for a relative roughness height of 3 compared to a smooth channel.

As mentioned in Figure 9, in a channel with a rough bed at a relative depth of 0.3 and a constant Froud number 2.61, increasing the width ratio from 1.2 to 1.5 results in approximately a 7.23% reduction in the secondary-to-primary depth ratio. Furthermore, with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 15.05%. With an increase in Froud number 3.72, increasing the width ratio from 1.2 to 1.5 leads to a reduction of approximately 10.04% in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 17.14%.In a channel with a rough bed at a relative depth of 0.4 and a constant Froud number 2.38, increasing the width ratio from 1.2 to 1.5 results in approximately a 6.33% reduction in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 14.15%. With an increase in Froud number 3.4, increasing the width ratio from 1.2 to 1.5 leads to a reduction of approximately 8.97% in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 16.24%.In a channel with a rough bed at a relative depth of 0.6 and a constant Froude number 2.45, increasing the width ratio from 1.2 to 1.5 results in approximately a 6.19% reduction in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 11.08%. With an increase in Froud number 3.26, increasing the width ratio from 1.2 to 1.5 leads to a reduction of approximately 8.30% in the secondary-to-primary depth ratio, and with an increase in the width ratio from 1.5 to 3, the secondary-to-primary depth ratio decreases by approximately 12.46%.

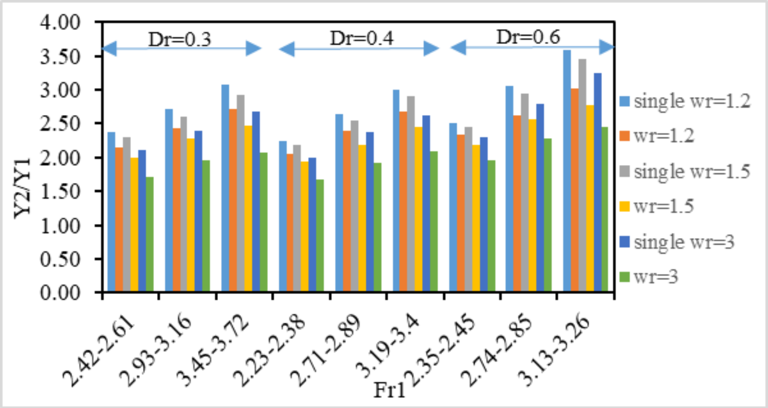

Figure 9. Illustrations of the ratio of $(\frac{Y_2}{Y_1})$ to the Froude number (Fr_1) for a relative roughness height of 5 compared to a smooth channel.

As it is clear from the examination of figures 7 to 9, based on these findings, it can be concluded that in channels with rough beds, increasing the width ratio results in a decrease in the secondary-to-primary depth ratio. Additionally, with an increase in relative depth in constant velocity, the secondary-to-primary depth ratio decreases. also with the increase of the relative depth (D_r) at a constant speed and roughness height ratio. (n_r) constant ratio of secondary depth to primary jump $(\frac{Y_2}{Y_1})$ decreases. By comparing the graphs with each other, it has been concluded that increasing the roughness height decreases the ratio of secondary to primary jump depth.

3.2. Relative length of hydraulic jump

In this section, we examine the ratio of jump length to secondary depth $(\frac{L_j}{Y_2})$ relative to Froude number (Fr_1) in a channel with a constant width ratio (w_r) and varying roughness height ratio (n_r). Figure 10 illustrates the ratio of jump length to secondary depth $(\frac{L_j}{Y_2})$ relative to Froude number (Fr_1) in a width ratio of 1.2. Increasing the Froude number results in a decrease in the ratio of jump length to secondary depth $(\frac{L_j}{Y_2})$. Generally, increasing the roughness height ratio (n_r) at a constant relative depth (D_r) and constant velocity leads to a decrease in the ratio of jump length to secondary depth $(\frac{L_j}{Y_2})$ in the absence of roughness. At a relative depth of 0.3, a roughness height ratio of 2, and Froud number 2.61, the ratio of jump length to secondary depth is approximately 5.22%. With a roughness height ratio of 3, the ratio decreases to about 11.25%, and with the highest roughness height ratio of 5, the ratio decreases to approximately 23.55% compared to the channel without roughness. Additionally, increasing the Froud number 3.72, the ratio of jump length to secondary depth decreases by approximately 10.45% with a roughness height ratio of 2, by about 17.76% with a roughness height ratio of 3, and by approximately 29.97% with a roughness height ratio of 5 compared to the case of a smooth channel. At a relative depth of 0.4, a roughness height ratio of 2, and Froud number 2.38, the ratio of jump length to secondary depth is approximately 4.57%. With a roughness height ratio of 3, the ratio decreases to about 9.90%, and with the highest roughness height ratio of 5, the ratio decreases to approximately 21.28% compared to the channel without roughness. Increasing the Froud number 3.4, the ratio of jump length to secondary depth decreases by approximately 8.22% with a roughness height ratio of 2, by about 14.52% with a roughness height ratio of 3, and by approximately 27.35% with a roughness height ratio of 5 compared to the case of a smooth channel. At a relative depth of 0.6, a roughness height ratio of 2, and Froud number 2.45, the ratio of jump length to secondary depth is approximately 2.20%. With a roughness height ratio of 3, the ratio decreases to about 8.04%, and with the highest roughness height ratio of 5, the ratio decreases to approximately 13.13% compared to the channel without roughness. Increasing the Froud number 3.26, the ratio of jump length to secondary depth decreases by approximately 5.50% with a roughness height ratio of 2, by about 12.32% with a roughness height ratio of 3, and by approximately 18.54% with a roughness height ratio of 5 compared to the case of a smooth channel.

In Figure 11, the ratio of jump length to secondary depth ($\frac{L_j}{Y_2}$) is shown relative to the Froude number (Fr_1) in a width ratio of 1.5 compared to a smooth channel. At a relative depth of 0.3, with a roughness height ratio of 2 and Froud number 2.61, the ratio of jump length to secondary depth is approximately 7.61%. With a roughness height ratio of 3, the ratio decreases to about 14.14%, and with the highest roughness height ratio of 5, the ratio decreases to approximately 26.28% compared to the smooth channel. Additionally, increasing the Froud number 3.72, results in a decrease of approximately 12.36% in the ratio of jump length to secondary depth with a roughness height ratio of 2, about 20% with a roughness height ratio of 3, and approximately 32.07% with a roughness height ratio of 5 compared to the smooth channel case. Similarly, at a relative depth of 0.4, with a roughness height ratio of 2 and Froud number 2.38, the ratio of jump length to secondary depth is approximately 6.57%. With a roughness height ratio of 3, the ratio decreases to about 13%, and with the highest roughness height ratio of 5, the ratio decreases to approximately 24% compared to the smooth channel. Increasing the Froud number 3.4, leads to a decrease of approximately 10.44% in the ratio of jump length to secondary depth with a roughness height ratio of 2, about 16.88% with a roughness height ratio of 3, and approximately 30% with a roughness height ratio of 5 compared to the smooth channel case. Lastly, at a relative depth of 0.6, with a roughness height ratio of 2 and Froud number 2.45, the ratio of jump length to secondary depth is approximately 4%. With a roughness height ratio of 3, the ratio decreases to about 10.85%, and with the highest roughness height ratio of 5, the ratio decreases to approximately 17.02% compared to the smooth channel. Increasing the Froud number 3.26 results in a decrease of approximately 7.19% in the ratio of jump length to secondary depth with a roughness height ratio of 2, about 14.39% with a roughness height ratio of 3, and approximately 20.41% with a roughness height ratio of 5 compared to the smooth channel case.

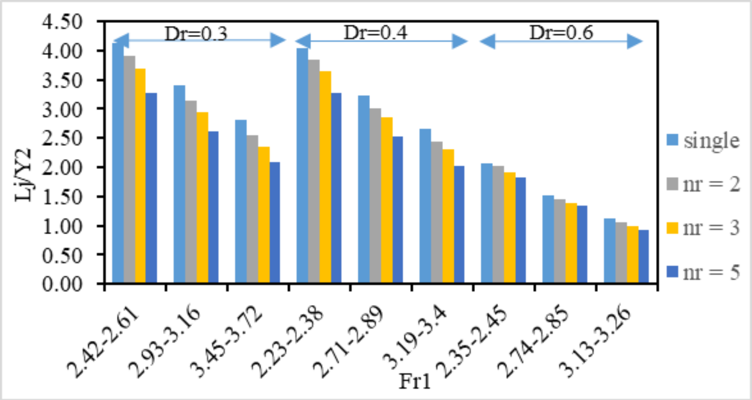

Figure 10. The ratio of $(\frac{L_j}{Y_2})$ to Froude number (Fr$_1$) in a width ratio of 1.2 (with a channel width of 18 cm) relative to a smooth channel.

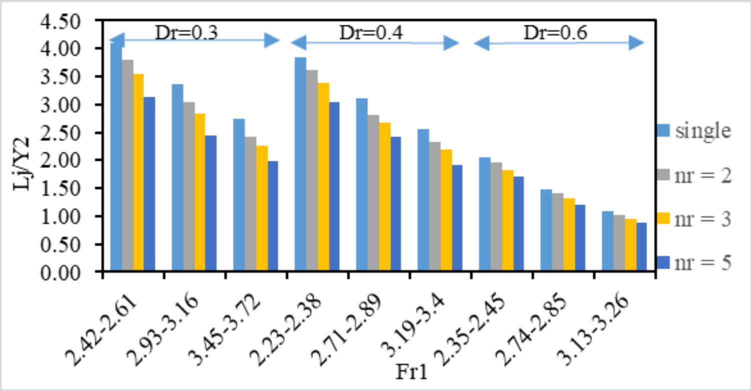

Figure 11. The ratio of $(\frac{L_j}{Y_2})$ to Froude number (Fr$_1$) in a width ratio of 1.5 (with a channel width of 22.5 cm) relative to a smooth channel.

In Figure 12, the ratio of jump length to secondary depth $(\frac{L_j}{Y_2})$ is presented relative to the Froude number (Fr$_1$) in a width ratio of 3 compared to a smooth channel. At a relative depth of 0.3, with a roughness height ratio of 2 and Froud number 2.61, the ratio of jump length to secondary depth is approximately 10.70%. With a roughness height ratio of 3, the ratio decreases to about 19.04%, and with the highest roughness height ratio of 5, the ratio decreases to approximately 30.7% compared to the smooth channel. Additionally, increasing the Froud number 3.72 results in a decrease of approximately 15.81% in the ratio of jump length to secondary depth with a roughness height ratio of 2, about 24.70% with a roughness height ratio of 3, and approximately 36.88% with a roughness height ratio of 5 compared to the smooth channel case. Similarly, at a relative depth of 0.4, with a roughness height ratio of 2 and Froud number 2.38, the ratio of jump length to secondary depth is approximately 9.52%. With a roughness height ratio of 3, the ratio decreases to about 17.76%, and with the highest roughness height ratio of 5, the ratio decreases to approximately 28.05% compared to the smooth channel. Increasing the froud number 3.4 leads to a decrease of approximately 14.23% in the ratio of jump length to secondary depth with a roughness height ratio of 2, about 21.65% with a roughness height ratio of 3, and approximately 35.13% with a roughness height ratio of 5 compared to the smooth channel case. Lastly, at a relative depth of 0.6, with a roughness height ratio of 2 and Froud number 2.45, the ratio of jump length to secondary depth is approximately 7.87%. With a roughness height ratio of 3, the ratio decreases to about 14.05%, and with the highest roughness height ratio of 5, the ratio decreases to approximately 26.29% compared to the smooth channel. Increasing the Froud number 3.26 results in a decrease of approximately 11.40% in the ratio of jump length to secondary depth with a roughness height ratio of 2, about 19.35% with a roughness height ratio of 3, and approximately 29.21% with a roughness height ratio of 5 compared to the smooth channel case.

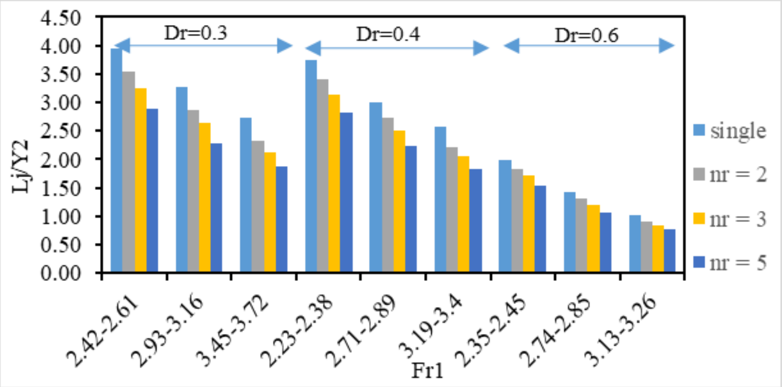

Figure 12. The ratio of $(\frac{L_j}{Y_2})$ to Froude number (Fr_1) in a width ratio of 3 (with a channel width of 45 cm) relative to a smooth channel.

As it is clear from the examination of figures 10 to 12, the increase in the width ratio (w_r) causes a decrease in the ratio of the jump length to the secondary depth $(\frac{L_j}{Y_2})$, also with the increase of the relative depth (D_r) in a roughness height ratio (n_r). The constant ratio of jump length to secondary depth $(\frac{L_j}{Y_2})$ decreases. An increase in the relative depth (D_r) causes an increase in the length of the jump $(\frac{L_j}{Y_2})$ and an increase in the Froude number in a fixed relative depth (D_r) causes a decrease in the length of the jump. By looking at the figures, we found that the increase in the ratio of the height of the roughness (n_r) causes a decrease in the ratio of the jump length to the secondary depth $(\frac{L_j}{Y_2})$ compared to the channel without roughness. It was also found that the lowest value in reducing the ratio of jump length to secondary depth $(\frac{L_j}{Y_2})$ occurs at a relative depth of 0.6 and a roughness height ratio of 2, because the height of the roughness is so small and the depth The entrance is large and the presence of roughness does not have much effect, but as the height ratio of roughness increases to 3 and 5, this change becomes more apparent. The highest value in the reduction of the ratio of jump length to secondary depth $(\frac{L_j}{Y_2})$ occurs in the relative depth of 0.3, especially in the roughness height ratio of 5 and the width ratio of 3 in the Froud number of 3.72.

4. Conclusions

The presence of roughness increases the Froude number. In a compound channel, as the floodplain width increases, the secondary jump depth and jump length decrease. In a compound channel with the same relative depth, increasing the Froude number leads to a decrease in jump length and an increase in secondary depth. At a constant velocity, as the relative depth (D_r) increases, the jump length also increases. The presence of irregular arrangement due to roughness causes a decrease in the secondary jump depth and jump length compared to when the channel is smooth. Increasing the height ratio of roughness leads to a decrease in jump length. The greatest decrease in jump length occurs at a relative depth of 0.3, roughness height of 5, and velocity of 5 m/s, while the least decrease in jump length occurs at a relative depth of 0.6, roughness height of 2, and velocity of 4.5 m/s. With increasing roughness height, the secondary depth decreases, but it was observed that increasing the roughness height has a negligible effect on the secondary depth compared to the increase in width ratio, which has a more noticeable impact on the secondary depth.

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Conflicts of Interest

The author declares no conflict of interest.

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