SUBMERGED HYDRAULIC JUMP CHARACTERISTICS ON ROUGH AND CORRUGATED BASINS

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ABSTRACT

In order to confine the location of hydraulic jumps and abbreviate the length of stilling basins, U-shaped corrugation, or granular gravels basin may be an alternative to the smooth basin. This paper examines the submerged hydraulic jump on smooth, rough and corrugated beds. Experiments were conducted to explore the influence of rough or corrugated beds on submerged jump length, backup depth, and bed shear force with different hydraulic parameters. Five different values of gate opening were used with different five values of Froude numbers. The smooth basin was also included to assess the performance of roughed and corrugated beds. A non-dimensional and regression analysis tools were applied to propose reliable formulas for estimating the hydraulic parameters. The results indicated that the corrugated beds had a significant reduction in the submerged jump length and consequently the size and cost of the stilling basins were reduced.

Keywords: Radial gate; submerged hydraulic jump; rough stilling basin; corrugated beds; jump length; backup depth; shear force.

1 INTRODUCTION

Radial gates are considered one of the most common water control structures in many irrigation networks in Egypt and worldwide. The flow through radial gates is classified as either free flowing or submerged depending upon the tail water depth and the size of the gate opening. Reviewing the literature revealed that, many researches were found on free radial gates (e.g. Toch 1955; Buyalski 1983; Clemmens et al. 2003; Bijankhan et al. 2011; Clemmens and Wahl 2012; Bijankhan et al. 2013; Ali et al. 2015; Abdelhaleem 2016; Abdelhaleem 2017; Basiouny et al. (2019); Ibraheem 2019), few works on submerged radial gates exist.

A hydraulic jump occurs in open channels when sudden, rapid transition from a supercritical flow to a subcritical flow. If the tailwater depth is equal the subcritical sequent depth is called a free hydraulic jump, the jump will be swept out of the basin, resulting in scour of the downstream channel. However, when the tailwater depth is greater than the subcritical sequent depth, the jump will become submerged. It has been observed that when the submergence of the jump increases, jet mixing decreases. This results in less dissipation of energy compared with free jumps, and the decay of the high velocity jet is retarded (Govinda Rao and Rajaratnam 1963; Rajaratnam 1965, 1967).

focused many researchers for the past several decades on hydraulic jumps, because of its prevalence in natural and open channel flows and other special applications such as mixing of chemicals, aeration of water etc. Among all these applications, energy dissipation is considered to be one of the most important applications for civil engineers. Various types of researches have been presented in literature for identification of the submerged hydraulic jumps properties on horizontal smooth beds, Rajaratnam (1967) was one of the leading researchers who carried out detailed studies to find out a relationship between submergence factor and energy dissipation. Subhasish and Bernhard (2003) have presented extensive study on the characteristics of turbulent flow in submerged jumps on rough beds. From the vector plots of the flow field, it was found out that the rate of decay of jet velocity in a submerged jump decreases with decrease in bed roughness.

Submerged jumps have been reported by many of researchers (e.g. Narasimhan and Bhargava 1976; Long et al. 1990; Leutheusser and Fan 2001; Dey and Sarkar 2008; Abdelhaleem 2017; Basiouny et al. 2018). The flow properties of submerged hydraulic jumps have been studied by numerous investigators (e.g. McCorquodale and Khalifa 1980; Ma et al. 2001; Abdel-Aal 2004; Bhuiyan et al. 2011; Ali et al. 2014).

A hydraulic jump could be controlled by sills of various shapes and rough bed. These structures ensure the formation of hydraulic jump and control its position for all operating conditions. Ead and Rajaratnam (2002) stated that, if jumps were made to occur on corrugated beds, significant reductions might occur in the required tailwater depth and length of the jumps. An employing laboratory investigation was performed with hydraulic jumps occurring on corrugated beds and the results obtained showed that this idea might be useful for energy dissipation for some of hydraulic structures. The roughness height was assumed equal to the sinusoidal corrugations. The rough beds have been studied by numerous investigators [e.g. Carollo et al. 2007, Kumar, and Lodhi 2015, Hassanpour, et al. 2017, and Ibraheem, et al. 2018].

El-Gamal (2011) experimentally investigated the effect of five different shapes including; semi-circular, trapezoidal, spaced trapezoidal, triangular, spaced triangular corrugated beds with free hydraulic jumps. Ali et al. (2014) highlighted the effectiveness of spaced triangular corrugated beds on dissipating energy of submerged hydraulic jumps.

Before applied rough and corrugated beds on the field, more investigations are needed especially with submerged hydraulic jumps downstream of radial gates. The submerged hydraulic jump is the most common in Egypt, so laboratory experiments were carried out using different heights of roughness elements and spaced semicircular corrugation sheets on the stilling basin with submerged hydraulic jump downstream a radial gate.

2 EXPERIMENTAL SETUP AND METHODOLOGY

The experiments were performed in the hydraulic laboratory of the Benha Faculty of Engineering, Benha University, Egypt. Measurements were conducted in a zero slope flume with smooth concrete bed and Plexiglas walls. The flume has a width of 0.4 m, height of 0.6 m, and length of 15.0 m. It has an adjustable tailgate at the downstream end to produce the submerged flow condition. At 7.0 m downstream of the entrance, a radial gate was installed. The radial gate was made of steel with sharp edge seal of 2.0 mm thickness. For all experiments, the radial gate radius was 470 mm, the trunnion-pin height was 230 mm, and the gate width was 400 mm as shown in Figure 1. The gate openings were set at 2, 2.5, 3, 4, and 5 cm, creating a supercritical stream. A Prandtl-type pitot-static tube with an outer diameter of 3 mm placed in the center of the flume was used to measure the backup water depth.

The channel bed was roughened using three different types of roughness elements; artificial (U-shaped corrugated bed), natural gravel, big gravel shown in Figure 1. The heights of the elements used in the experiments were 22, 29, 41, and 51 mm. The length of the roughened bed was limited to 1.2 m downstream of the radial gate. The roughness elements were kept to the full width of the flume. In addition, the spacing between U-shaped elements equals double roughness height was during experiments.

A total 160 runs were performed, during the course of the experiments, all different cases were tested under the same flow conditions. The range of the experimental data were as follows: flow discharge Q = (16-30 l/s), Froude number = (4.03-8.23), Submergence ratios (S = 0.1, 0.2, 0.3, and 0.4), the submergence ratios is defined as $S = (y_t - y_2)/y_2$, where y_2 is the subcritical sequent depth for a submerged jump corresponding to the supercritical depth of y_1.The super critical depth, y_1 was measured at a distance of 1.15 times the gate opening from the gate; this is the approximate location of the vena contracta, Narasimhan and Bhargava (1976). The values of discharge and the gate opening were adjusted to the desired for the flow conditions. When the flow became at the steady state conditions, the upstream water depth, and the tailwater depth were measured.

3 RESULTS AND DISCUSSION

The water entrains a significant amount of air as it passed from the gate opening. Momentum causes the air entrained water to travel downstream of a radial gate. Once the buoyant force of the entrained air can overcome the inertial forces of the water, it will begin to rise. The force of the rising air creates a strong current. By the time this current has reached the surface it may be a significant distance downstream of the radial gate. Some of this water that has been forced to the surface will double back toward the radial gate structure creating an upstream current on the surface of the water. Energy is being dissipated, but the headwater does not have enough energy to push the tailwater away from the face of the structure.

3.1 Length of Submerged Jump

For the submerged jumps, jump characteristics are function of submergence ratio, S the relative roughness height, k_s/y_1 and Froude number at vena contracta F_1. In Fig. 2, relative length of submerged jumps L_j/y_1 is plotted versus F_1 for the considered heights of rough beds and corrugated beds at different submergences. According to this figure, the relative length of submerged hydraulic jump increases as the submergence factor increases. For the same submergence ratio, the length of the submerged hydraulic jump increases as the Froude number increases. This indicates that the submergence ratio and Froude number are the most significant influential factor on the length of the submerged hydraulic jump. The length of submerged hydraulic jump over the rough beds is smaller than the corresponding length of jump over smooth bed. For the considered submergence ratios, the jump length decreases as the roughness height increases. In other side, the length of hydraulic jump over the corrugated beds is smaller than the corresponding length of jump over rough beds, due to direction of water velocities and the vortex faster moves to a surface.

Employing the experimental data compiled in the current study and applying the regression analysis, L_j/y_1 and other independent parameters are correlated to develop the following formulas:

$$L_j / y_1 = 10.48\ F_1^{0.878}\ S^{0.116} \tag{1}$$

$$L_j / y_1 = 7.185\ F_1^{0.708}\ S^{0.101}\left(\frac{k_s}{y_1}\right)^{-0.056} \tag{2}$$

$$L_j / y_1 = 6.551\ F_1^{0.949}\ S^{0.071}\left(\frac{k_s}{y_1}\right)^{-0.116} \tag{3}$$

Eq. (1) is valid for submerged radial gates with smooth bed and Eqs. (2) and (3) are proposed for submerged radial gates with corrugated and rough beds, respectively. The coefficients of determination R^2 of Eqs. (1), (2), and (3) was remarkably high (R^2 = 97, 93.76, and 95.35%, respectively). In figure 3, the comparison between the calculated values of the ratio L_j/y_1 by present study Equation (1) for smooth bed with Hassanpour, et al. (2017), Abdelhaleem (2017), Velioglu, and Tokyay (2012), Subramanya (2009), and Ayanlar (2004) at these conditions; Hassanpour, et al. (2017) classical hydraulic jump range of Froude numbers ranging from 6 to 12 with smooth bed, Abdelhaleem (2017) submerged hydraulic jump over smooth bed downstream a radial gate, Velioglu, and Tokyay (2012) classical hydraulic jump over smooth bed range of Froude numbers ranging from 3 to 10, Subramanya (2009) free hydraulic jump over smooth bed, Ayanlar (2004) hydraulic jump on smooth bed with Froude numbers ranging from 4 to 12. It is clear that the present study were in a good agreement with those carried out by Abdelhaleem (2017) because of that study at the same conditions. According to Fig. 3 current experimental data were in a good agreement with those carried out by Abdelhaleem (2017), and Subramanya (2009).

Figure 4 shows the comparison between the calculated values of the ratio L_j/y_1 by present study Equations (2), and (3) for corrugated, and rough beds with Hassanpour, et al. (2017), Abdelhaleem, et al. (2012), Velioglu, and Tokyay (2012), Carollo et al. (2007), and Ayanlar (2004) at these conditions; Hassanpour, et al. (2017) classical hydraulic jump range of Froude numbers ranging from 6 to 12 with rough bed, Abdelhaleem, et al. (2012) free hydraulic jump over corrugated bed downstream a sluice gate with wide range of Froude numbers ranging from 2.0 to 6.5 and Five values of the relative roughness, Velioglu, and Tokyay (2012) classical hydraulic jump over corrugations, gravels beds range of Froude numbers ranging from 3 to 10, Carollo, et. al. (2007) free hydraulic jump and rough bed with different roughness height from 0 to 3.2 cm and F_1 from 1.87 to 9.89, Ayanlar (2004) hydraulic jump on corrugated bed with Froude numbers ranging from 4 to 12. According to Fig. 4 for present study the jump length is lower using corrugated bed than natural rough bed. Submerged radial gate have negative impact on the submerged flow characteristics. It is clear that the present study over rough bed were in a good agreement with those carried out by Velioglu, and Tokyay (2012) and Carollo, et al. (2007) at small Froude numbers. It is clear that the present study over rough bed were in a good agreement with those carried out by Ayanlar (2004).

3.2 Backup Depth

In Fig. 5, the relative backup depth y_3/y_1 is plotted versus F_1 for smooth, corrugated and rough beds at constant S value. This figure shows that for some tested roughness heights, the relative backup depth y_3/y_1 increases as S value increases. For constant w and y_t, the relative backup depth y_3/y_1 increases as the roughness height increases. This signifies that increasing the roughness height increases the submergence of the incoming jet and increases the energy loss.

The backup water depth over the rough beds is higher than the corresponding backup water depth over smooth bed. For the considered submergence ratios, the jump length increases as the roughness height increases. In other side, the backup water depth is lower using natural rough bed than corrugated bed. The backup water depth over the corrugated and rough beds increases as roughness height k_s increases by small rate, due to direction of water velocities and the vortex moves to a surface by any roughness height. The backup water depth is extremely difficult to measure in the field while the flow is highly turbulent. In an attempt to simplify the field measurements, the experimental data were employed and applying the regression analysis tools to propose the following equations:

$$y_3 / y_1 = 1.517\ F_1^{1.168}\, S^{0.246} \quad (4)$$

$$y_3 / y_1 = 1.767\ F_1^{1.064}\, S^{0.138} \left(\frac{k_s}{y_1}\right)^{0.101} \quad (5)$$

$$y_3 / y_1 = 1.752\ F_1^{1.062}\, S^{0.2} \left(\frac{k_s}{y_1}\right)^{0.086} \quad (6)$$

Eq. (4) is valid for submerged radial gates with smooth bed and Eqs. (5 and 6) are proposed for submerged radial gates with corrugated beds and rough beds, respectively. The predictive capability of Eqs. (4), (5), and (6) was remarkably high (R^2 = 98.48, 98.35, and 98.28%, respectively) where: R^2 the coefficient of determination. In figure 6, the comparison between the calculated values of the ratio y_3/y_1 by present study Equations (4), (5), and (6) for smooth, corrugated, and rough beds with Habibzadeh, et al. (2011), and Govinda Rao and Rajaratnam (1963) at these conditions; Habibzadeh, et al. (2011) submerged jump with baffle walls and blocks downstream of a sluice gate was conducted, Govinda Rao and Rajaratnam (1963) submerged hydraulic jump over smooth bed without any blocks. According to Fig. 6, Eq. (4) is in a very good agreement with experimental study given by Habibzadeh, et al. (2011). Although the equation is developed for submerged jump with baffles walls and blocks downstream of a sluice gate, the present study applied this equation into its calculation procedure for submerged radial gates.

3.3 Bed Shear Stress

One of the main objectives of installed corrugated or rough beds is to increase the bed shear stress, improve the sequent water depth and the length of the hydraulic jump thus is leads to reduce length of stilling basin. In the present section, the bed shear force (F_τ) is calculated using the momentum equation as following:

$$F_\tau = (P_1 - P_2) + (M_1 - M_2) \qquad (7)$$

Where: P_1, P_2, M_1 and M_2 are the integrated pressures and momentum fluxes at sections prior and after the hydraulic jump, respectively. Also the shear force index ε_1 can be written as:

$$\varepsilon_1 = F_\tau / M_1 \qquad (8)$$

The shear force index is extremely impossibility to measure in the field. In an attempt to simplify the field measurements, the experimental data were employed and applying the dimensional analysis tools to propose the following equations:

$$\varepsilon_1 = 0.133\ F_1^{0.608}\, S^{-0.114} \qquad (9)$$

$$\varepsilon_1 = 0.513\ F_1^{0.156}\, S^{-0.07} \left(\frac{k_s}{y_1}\right)^{0.276} \qquad (10)$$

$$\varepsilon_1 = 0.309\ F_1^{0.219}\, S^{-0.067} \left(\frac{k_s}{y_1}\right)^{0.307} \qquad (11)$$

Figures (7, 8) show the variation of shear force coefficient (ε_1) with F_1 for submerged jumps on different beds along with the mean curve for free jumps formed on corrugated beds for a range of Froude numbers from 4 to 10 Ead and Rajaratnam (2002). The relationship between shear force index (ε_1) and F_1 is illustrated in Figure 7, it is apparent that from this figure that shear forces over artificial corrugated beds are bigger than natural rough beds and smooth bed. The average shear stress Calculated by Eq. (10) for submerged jumps over corrugated beds is about two times of those calculated by Ead and Rajaratnam (2002).

4 CONCLUSIONS

Based on the experimental investigations of the submerged hydraulic jumps produced through a radial gate on smooth, corrugated and rough beds, the following conclusions are highlighted:

- Submerged radial gates with smooth bed needs longer stilling basin than the rough or corrugated beds.

- The corrugated and rough beds reduce the length of hydraulic jump by 48% and 28%, respectively in comparison with the smooth bed.
- The corrugated and rough beds increase the backup water depth by about 20%, and 12% respectively, in comparison with the smooth bed.
- The corrugated and rough bed increase the shear force index in comparison with the shear force index exerted on the smooth bed by 78% and 19%, respectively.
- Although, the corrugated beds enhanced the efficiency of the submerged hydraulic jump better than the rough beds, rough beds remain economically wise.
- Throughout this investigations, statistical equations were deduced to estimate the jump length and the backup depth, and they agreed well with those available in the literature. The developed equations are applicable within the tested range in current experiments.

NOTATION

The following symbols are used in this paper:
a: gate trunnion-pin height;
B: channel width;
F_1: initial Froude number;
F_τ: total shear forces;
k_s: roughness height;
L: length of stilling basin;
L_j: length of submerged hydraulic jump;
M_1: momentum flux, at section where jump starts;
M_2: momentum flux, at section where jump ends;
Q: flow discharge;
P_1: hydrostatic force, at section where jump starts;
P_2: hydrostatic force, at section where jump ends;
R^2: the coefficient of determination;
r: radius of the radial gate;
S: submergence factor;
w: gate opening;
y_o: upstream water depth;
y_1: water depth at vena contracta (minimum jet thickness);
y_2: sequent depth of submerged hydraulic jump;
y_3: backup water depth downstream of the gate;
y_t: tailwater depth;
θ: gate leaf angel; and
ε_1: shear force coefficient.

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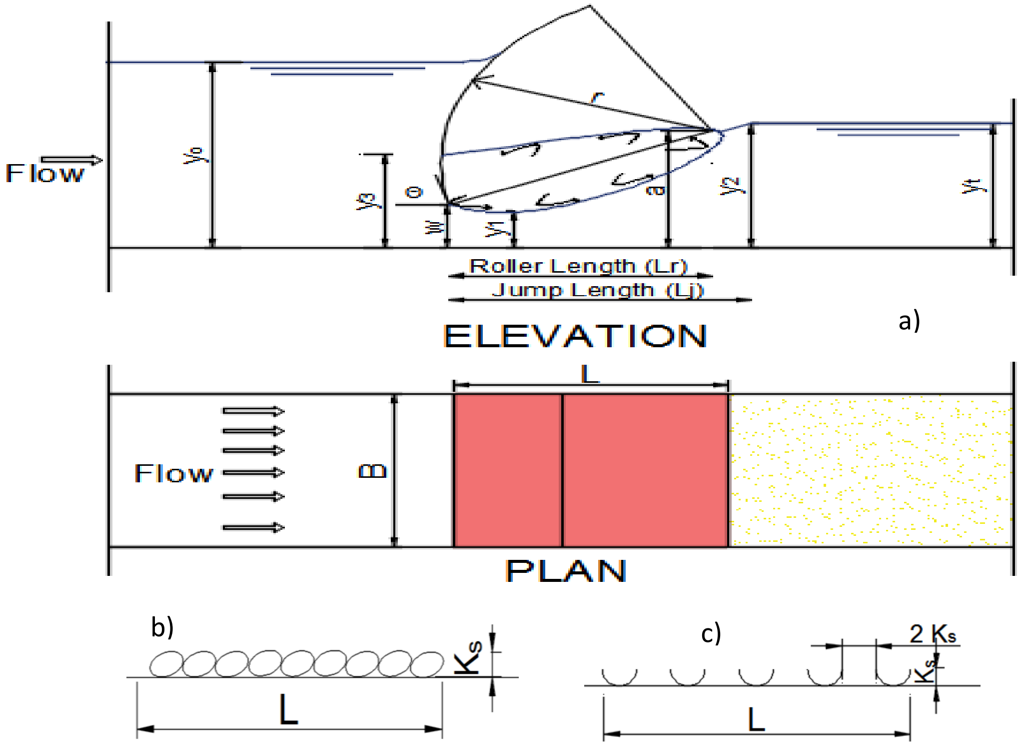

Figure 1. a) A Sketch of a submerged hydraulic jump downstream radial gate on smooth bed b) rough bed c) corrugated bed.

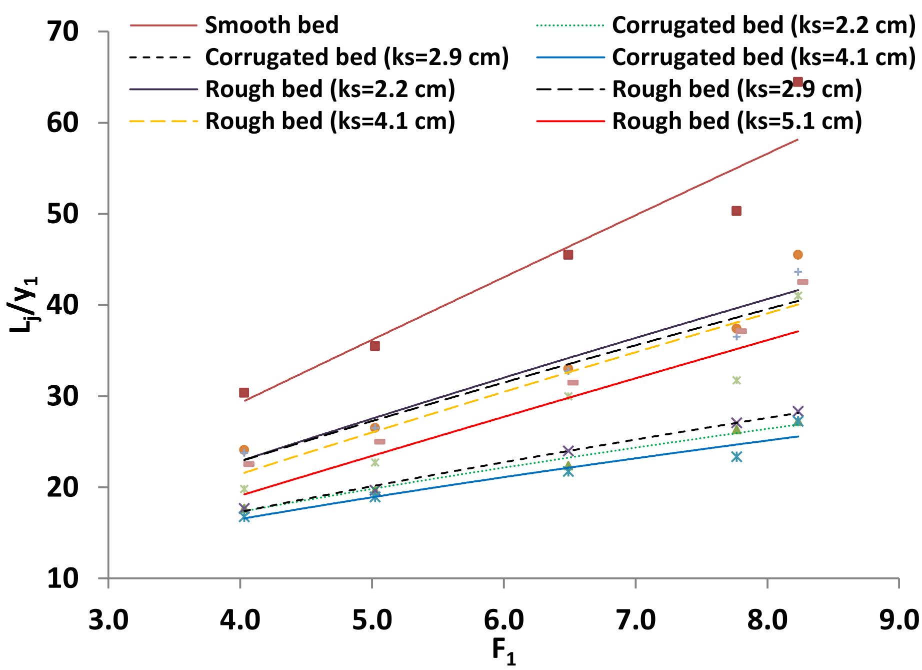

Figure 2. Relationship between observed values of ratio (L_j/y_1) with observed F_1 at S = 0.3

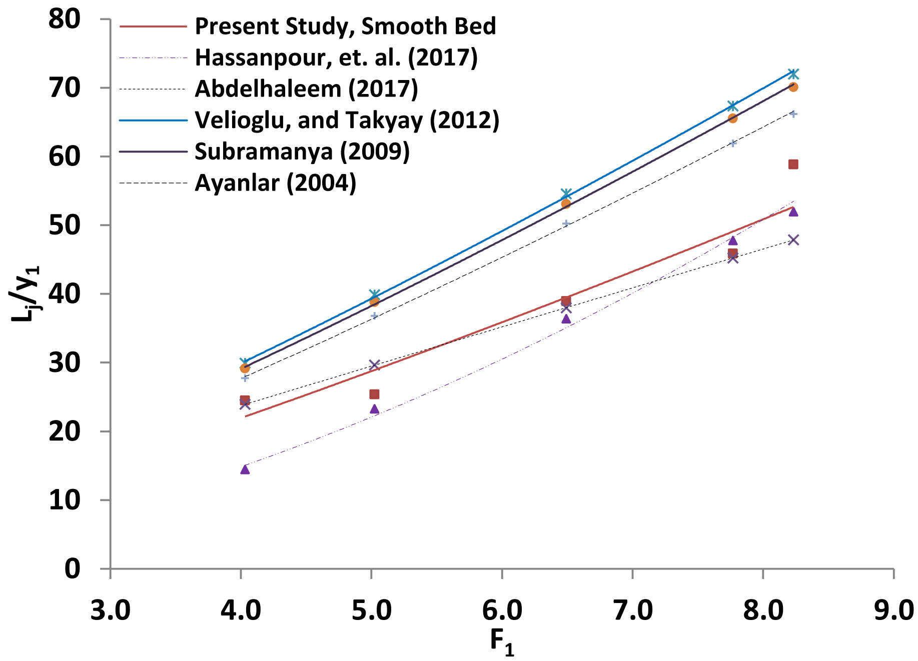

Figure 3. Relationship between the length ratio (L_j/y_1) and F_1 for previous research works and the present study for smooth bed.

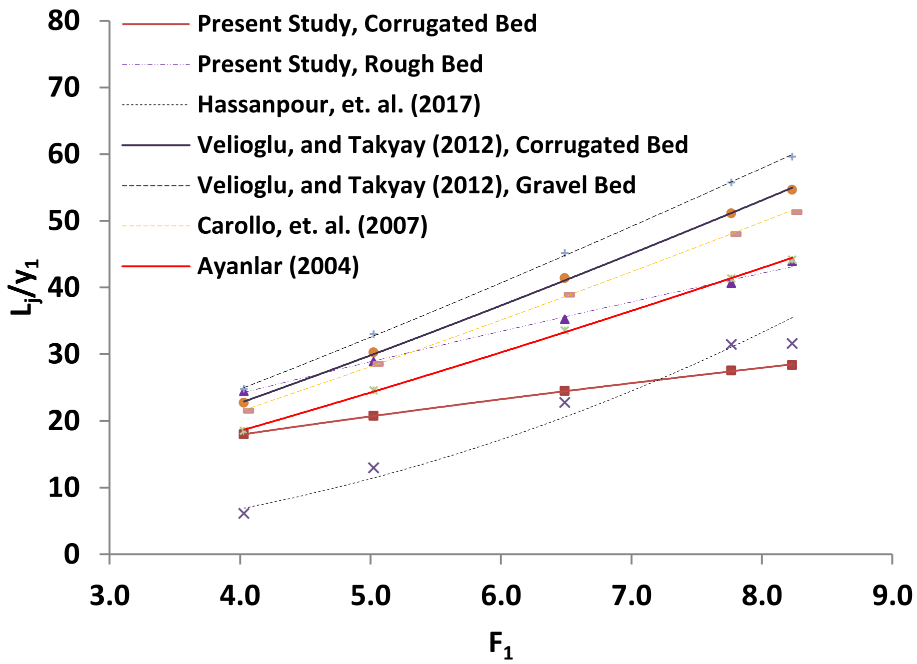

Figure 4. Comparison between (L_j/y_1) values measured in the present study and those of previous research for rough and corrugated beds.

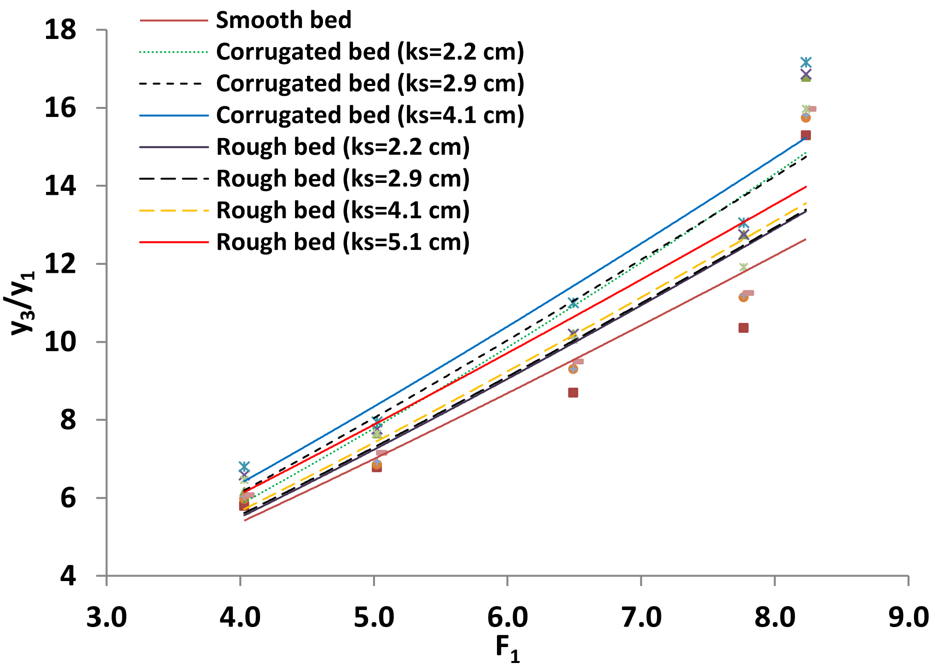

Figure 5. Relationship between observed values of ratio (y_3/y_1) with F_1 for different smooth, corrugated and rough beds at S = 0.3

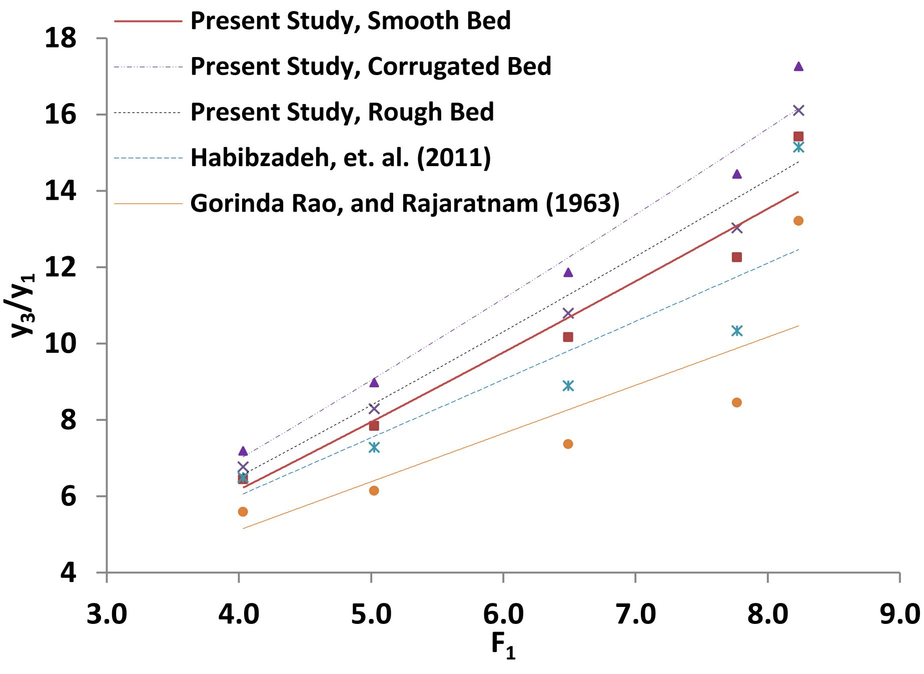

Figure 6. Comparison between measured (y_3/y_1) in the present study and other of previous studies in case of rough, corrugated, and rough beds.

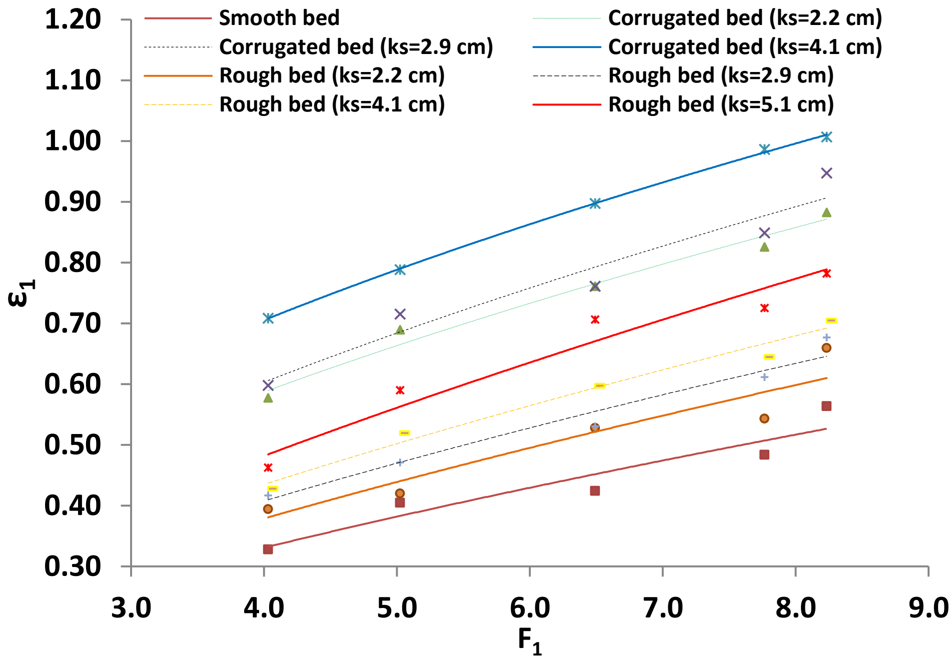

Figure 7. Relationship between observed values of ratio (ε_1) with observed F_1 for smooth, rough and corrugated beds at S = 0.4

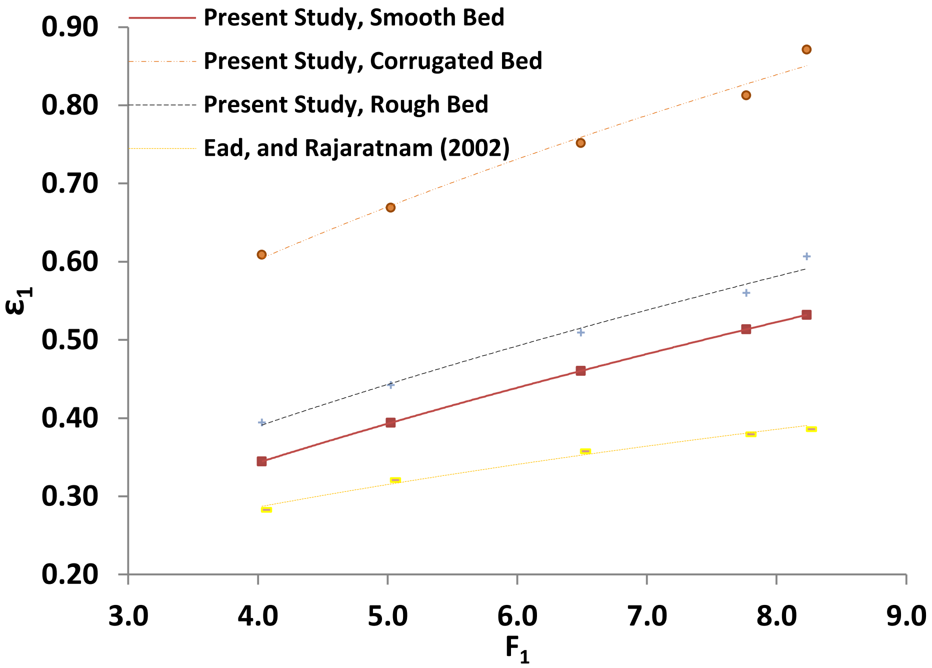

Figure 8. Relationship between the shear force coefficient (ε_1) and F_1 for previous research works and the present study for smooth, rough, and corrugated beds.