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Effect of corrugated beds on characteristics of submerged hydraulic jump

Hossam Mohamed Ali Ahmed [a,*], Mohamed El Gendy [b], Ahmed Mohamed Hassan Mirdan [c], Abdel Azim Mohamed Ali [d], Fahmy Salah Fahmy Abdel Haleem [d]

[a] *North Sinai Development Sector, Ministry of Water Recourses and Irrigation, Cairo, Egypt*
[b] *Geotechnical and Foundation Engineering, Faculty of Engineering, Port Said University, Port Said, Egypt*
[c] *Irrigation Engineering, Faculty of Engineering, Port Said University, Port Said, Egypt*
[d] *Hydraulics Research Institute, National Water Research Center, Ministry of Water Resources and Irrigation, Cairo, Egypt*

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KEYWORDS

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Jump efficiency and sequent depth

Abstract Hydraulic jump is generally helped in the dissipation of excess kinetic energy downstream of hydraulic structures such as gates, spillways, and weirs. This paper presents a comprehensive review of the available literature on the hydraulic jump properties on corrugated beds. In the present study the effect of spaced triangular strip corrugated bed on submerged jump characteristics has been experimentally investigated. Thirty experimental runs were carried out considering wide range of Froude numbers ranging from 1.68 to 9.29. Experiments were conducted for both smooth and rough bed. The results confirm that sequent depth and jump length were reduced by average values 15.14% and 21.03%, respectively, whereas, jump efficiency was increased by 50.31% at optimum spaced roughness compared to a classical jump respectively. Dimensionless relationships were deduced to predict the jump characteristics. Results of the present study were agreed satisfactorily with the previous studies.

1. Introduction

Hydraulic jump occurs when a high velocity supercritical flow drops to that of a subcritical flow, the rapid following flow is abruptly slowed and increases its height, converting some of the kinetic energy into potential energy. The condition of occurrence of a hydraulic jump is to change flow suddenly from supercritical flow (low depth with high velocity) to subcritical flow (high depth with a low velocity), Chow [1]. It also happens when slope changed from steep to mild slope. Hydraulic jump is a useful phenomenon in open channel hydraulic. It is generally used for the dissipation of excess kinetic energy downstream of hydraulic structures such as drops, spillways, chutes and gates, increasing weight on an apron and thus reduce uplift pressure under control structures,

* Corresponding author. Tel.: +20 01006566037.
E-mail address: h_aly28@yahoo.com (H.M.A. Ahmed).
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Nomenclature

b	The base width of corrugated bed,	t	The height of corrugated bed,
D	Dimensionless index,	v	Flow velocity before the jump,
E_1	Specific energy at the initial water depth of a hydraulic jump,	R	Reynolds's number,
E_2	Specific energy at the sequent water depth of a hydraulic jump,	y_1	Initial water depth of hydraulic jump,
F_r	Froude number at initial water depth,	y_2	Sequent water depth of hydraulic jump,
g	The acceleration of gravity,	y_2^*	Subsequent subcritical flow for classical jump,
H_u	Upstream water depth	y_3	Submerged water depth,
L_j	Hydraulic jump length,	ρ	Density of the fluid,
L_r	Roller hydraulic jump length,	ν	Viscosity of the fluid,
S	Strip corrugations wave length,	γ	Unit weight of water,
		η	Hydraulic jump efficiency.

also, it can be used as a mixed tool in water supply and aerate water for city water supplies.

Hydraulic jump is divided into two types according to their bed characteristics. The first type is a classical hydraulic jump with a smooth bed, and the second type is a forced hydraulic jump. The first type has been extensively studied by Peterka [2], Rajaratnam [3], McCorquodale [4], Hager [5] and Sholichin and Akib [6]. If $y_1$and v_1 are, respectively, the depth and mean velocity of the supercritical stream just upstream of the jump, with the Froude number $F_r = v_1/\sqrt{gy_1}$ where g is the acceleration due to gravity. The subcritical sequent depth $y_2\,j$ is given by the well-known Belanger equation:

$$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1+8F_r^2}-1\right) \tag{1}$$

Hydraulic jump on rough beds has been also studied by many researches. Rajaratnam [7] carried out the first systematic studies on the hydraulic jumps over rough bed. He proved that the roller length L_r and the jump length L_j upon rough bed would decrease significantly in comparison to the smooth bed. Leutheusser and Schiller [8] also conducted studies upon the incoming jet over rough surfaces. They found that the existence of a developed supercritical flow downstream of the gates or spillways upon rough bed requires less length in comparison to smooth bed. Mahmoud [9] and Abdelsalam et al. [10] found that the optimal bed roughness intensity of cubic shape is 10% from both the hydraulics and economical point of view. Aboulatta [11] used the previous intensity to study the effect of location and length of roughened beds on flow characteristics.

Negm et al. [12] used two types of roughness element, they found that 13% and 16% roughness intensities provide the minimum relative jump length when hexagonal and cylindrical roughness elements were used for roughening the bed respectively. Alhamid [13] conducted experiments on a rough bed using cubic blocks. He concluded that 12% roughness intensity provided the optimal length of the basin for the flow conditions and roughness arrangement under consideration. Hughes and Flack [14] carried out experimental research on hydraulic jumps upon rough bed. They found that boundary layer roughness will definitely decrease the subcritical depth and length of the jump and the extent of this decrease are related to the Froude number and relative roughness of the bed.

Ead and Rajaratnam [15] performed an experimental study upon hydraulic jumps over round shape corrugated bed. Froude numbers ranging from 4 to 10 were taken into account and the value of the relative roughness was considered as being between 0.25 and 0.5.

They observed that the tailwater depth required for the hydraulic jump over corrugated bed is less than that required for jumps over smooth bed. It was also observed that the length of the jump is approximately half of that which occurs over smooth bed. Carollo et al. [16] measured the hydraulic jump characteristics on bed roughened by closely packed crushed gravel particles cemented to the bottom. They concluded that the boundary roughness reduces both the sequent depth and the length of a hydraulic jump and that the observed reductions were related to both Froude number and the degree of roughness. Pagliara et al. [17] studied the parameters that affect the sequent depth and the length of the hydraulic jump over homogenous and non-homogenous rough bed channels downstream of block ramps. They proposed a new relationship to determine the correction coefficient for the general jump equation for both uniform and non-uniform rough beds. Bejestan and Neisi [18] studied the effect of lozenge roughness shape on the hydraulic jump. They found that this shape reduces the tailwater depth by 24% and the hydraulic jump length by 40% compared with smooth bed Ead et al. [19] performed tests on the changing of the velocity field in turbulence flows under different characteristics. The hydraulic engineers take care in design calculation development, the size and location of a hydraulic jump, Streeter et al. [20]. More studies and researches on hydraulic jump have been done such as Bakhmeteff and Matzke [21] and Narasimhan and Bhargava [22]. They found that the length of a hydraulic jump increased as depth increases with the increase in Froude number.

El-Azizi [23] studied theoretically the effect of different intensities of bed roughness on the rectangular submerged hydraulic jump. It was noticed that, the theoretical curve for all verification cases is almost lower than the experimental one. In addition to the above, McCorquodale and Kalifa [24], Abdel Gawad et al. [25], Smith [26] and Ohtsu et al. [27] analyzed the submerged hydraulic jump formed in a radial stilling basin provided with sudden drop both theoretically and experimentally. Both the experimental results and the developed equations indicated that at a particular relative location of the drop, the relative water depth, relative energy loss and relative length of jump increase by increasing Froude number keeping the submergence unchanged. Ezizah et al. [28]

conducted experimental work using a new shape of roughness U-shape. They found that the U-shape roughness is better than the cubic shape from hydraulic point of view as it decreases the hydraulic jump characteristics with considerable values compared to cubic roughness shape. Tokyay et al. [29] performed experiments to determine the effects of corrugations and prismatic roughness elements on hydraulic jump characteristics. They found that using prismatic roughness elements significantly reduced the jump length and jump sequent depth and induced more energy dissipation compared to a classical jump. An experimental study was conducted to study the effect of using three different shapes of corrugated beds on the characteristics of a hydraulic jump by Abdelhaleem et al. [30]. They found that the triangular shape of corrugation has highly decreased the required tail water depth. In conclusion, the review of the previous published materials showed that the corrugated beds can effectively decrease the required conjugate depth and length of the jump, thus it can reduce the cost of the stilling basins.

The present study is thus an attempt to extend the previous studies by investigating the effect of strip triangular corrugated bed shapes downstream of heading-up structures. From the authors' point of view, the studies which were conducted on submerged hydraulic jump are too few but rather rare especially on corrugated beds so this research may be a good starting point for the study by applying an experimental investigation. The findings may be used to describe the influences of various parameters of the submerged hydraulic jump characteristics over corrugated beds.

2. Experimental setup

In order to reach the main purpose of this research, a model of a streamlined-lip gate with horizontal basin is used to develop the required supercritical flow and initial depth of the jumps. The model is investigated experimentally with smooth bed to use its results as a reference case to the cases of corrugated beds. To create the required roughness of the bed, aluminum triangular sheets were installed on the flume bed, and in order to diminish the effects of cavitation, the crests of corrugation were set at the same level of upstream bed, as shown in Fig. 1. The corrugations acted as depressions in the bed, to create a system of turbulent eddies which might increase the bed shear stresses.

The dimensions of the corrugated sheet beds are: The triangular corrugated sheet of 40-mm height and 40-mm width and with side angles of 45° is kept constant. The experiments have been conducted in the hydraulic laboratory flume of the Hydraulics Research Institute (HRI), National Water Research Center (NWRC). The flume is constructed of bricks sealed with smooth cement mortar except part of Plexiglas sides with length of 2.25 m to facilitate the observation process.

The flume is 0.75 m wide, 0.70 m deep and 24.5 m long. A centrifugal pump is used to supply water to the head tank from the storage tank. The head tank has a gravel box which is used to provide an even flow distribution across the flume as shown in Figs. 2 and 3. To control the water flow rate, a gate valve is installed on the supply pipe line just before the head tank. The downstream bay is made of wood with length 2.5 overlaid on a 0.5 m layer of sand to prevent leakage, this bay represents the smooth bed also, prepared for the corrugated sheets fixation. Water depths and bed levels were measured by a point-gauge. The gauge is mounted on carriage moving in the flow and the perpendicular directions. Downstream water depth is controlled using a tail gate in order to form jumps over the rigid bed, and then, the water flowed to the by-pass channel. The length of floor and dimensions of corrugated sheets are kept constant for all runs, whereas, the distance between corrugated sheets is changed to achieve the optimal spacing.

To achieve the main purpose of this research, two discharges are considered (Q = 30 and 45 l/s). The discharge was measured by Ultrasonic-Flow meter which located at the supply lines. Initial water depth (y_1) equal to 3.86, 2.99 and 2.02 cm is used with discharge 30 l/s whereas 2.15 and 1.62 cm are used with discharge 45 l/s. All types of submerged hydraulic jumps according to classification of Chow [1] were investigated. Thirty runs were carried out including 5 runs with smooth bed. These five smoothed bed runs were considered as a reference case. For each run, the backwater feeding is started first until its depth reaches higher than the required downstream water depth, and then, the upstream feeding is pumped. To adjust the tail water depth, the tail gate is screwed gradually until the considered depth is adjusted. A point gauge is used to adjust the initial depth of jump, (gate opening) and is used to measure the sequent depth. Both the total jump length and the roller length are measured by a precise scale.

3. Results and dicussion

3.1. Conjugated depth

For hydraulic jump over corrugated beds with a supercritical depth (y_1), the sequent depth of the jump (y_2) can be written to be a function of:

$$f(y_1, v_1, g, \rho, \vartheta, t, b, S) = 0 \tag{2}$$

where g is the gravitational acceleration (ρ), θ is the density and viscosity of water, respectively, and other variables have been previously defined. By the application of Buckingham's theory, the dimensionless relationship thus, may be written as:

$$\frac{y_2}{y_1} = f\left\{F_r = \frac{v_1}{\sqrt{gy_1}}, R_n = \frac{v_1 y_1}{\vartheta}, \frac{b}{y_1}, \frac{t}{y_1}, \frac{S}{y_1}\right\} \tag{3}$$

For all experimental work, value of Reynolds's number R_n > 2500, so the effect of viscosity is considered to be neglected, then the values of Reynolds's number can be eliminated from analysis. Izadjoo and Shafai-Bajestan [31], Tokyay [32] and Ead [33] are concluded that, the relative roughness has a small influence on the sequent depth ratio, so the relation between initial Froude number (F_r) and (y_2/y_1) for the considered different spaced corrugated sheets is plotted, as shown in Fig. 4.

Generally, for considered spaced corrugated beds, the relative sequent depth is smaller than that of smooth bed. The results indicate that, the minimum values of relative sequent depth occurred at spacing between corrugated sheets S = 3t = 12 cm (where t is the triangular corrugated sheet height). One can see that, for the considered flow conditions, at optimal spaced triangular corrugated beds (S = 12 cm), the relative sequent depth decreases by 17.25%, 16.12%,

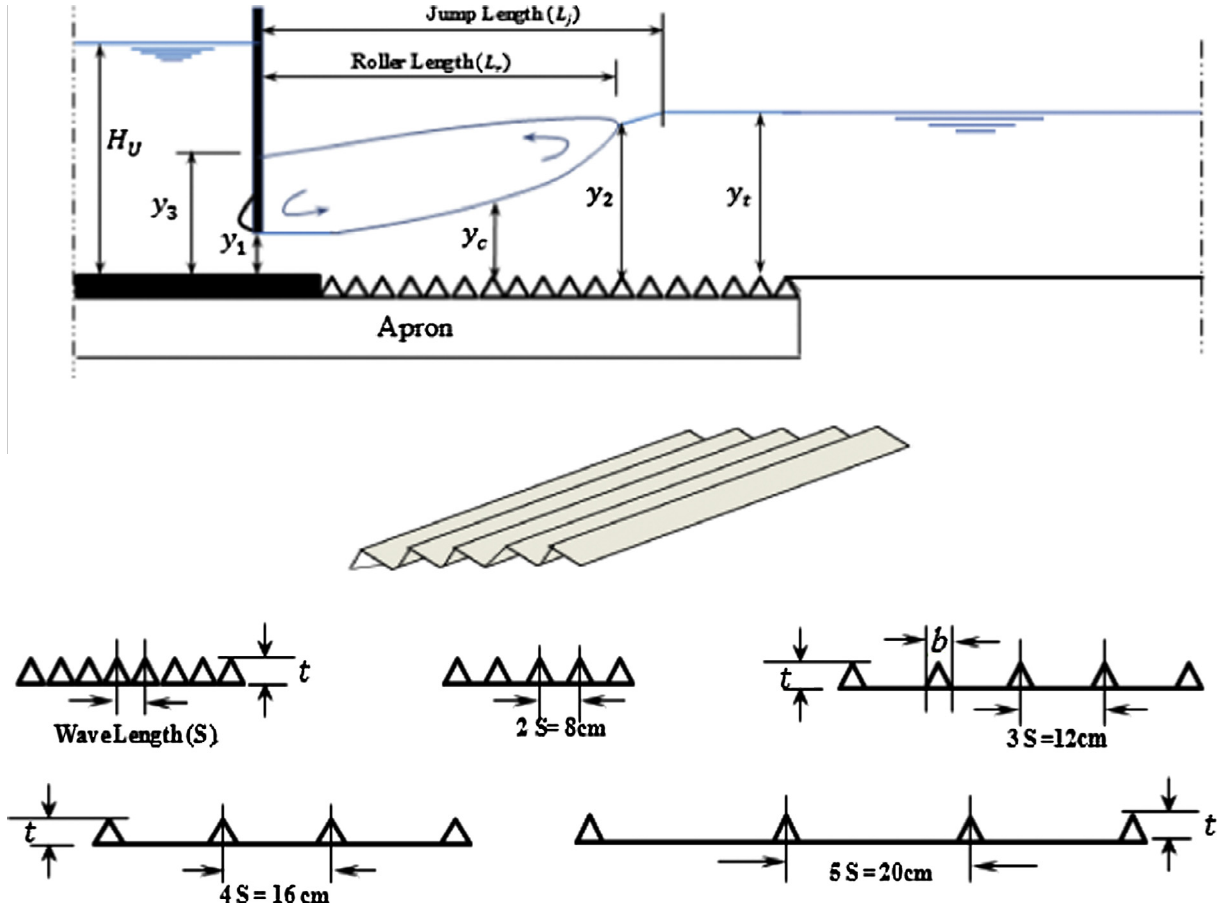

Figure 1 Schematic view of submerged jump and spaced corrugated beds.

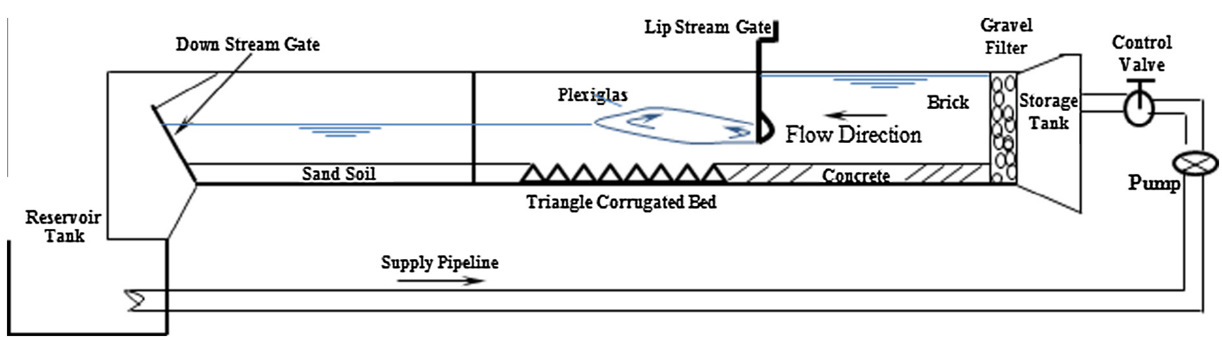

Figure 2 General side view of experimental flume.

15.04%, 14.47%, and 12.84% in comparison with that of the smooth bed for F_r = 1.68, 2.47, 4.45, 6.08 and 9.29 respectively. Statistical analysis of the results for (y_2/y_1) and (F_r) provides us with the following equation:

$$y_2/y_1 = 1.007(F_r)^{1.0844} \quad R^2 = 0.99 \tag{4}$$

Fig. 5 shows the comparison between the developed equation of present study at optimal spaced corrugated bed and the equations of previous studies. The present equation is in good agreement with Izadgoo and Shafai-Bajestan [31], Tokyay [32], and Abdelhaleem et al. [30].

3.2. Submerged ratio

Fig. 6 shows the relationship between the initial Froude number (F_r) and the submerged ratio of jump (y_3/y_1) at each spacing S = (4, 8, 12, 16 and 20) cm. From this figure, it is noticed that, generally, the submergence depth of jump (y_z) over strip corrugated bed sheets is small than that over smooth bed.

At optimal spaced corrugated beds $S = 3t = 12$ cm for all types of submerged jump i.e. F_r = 1.68, 2.47, 4.45, 6.08 and 9.29 the relative submerged jump decreases by 18.67%, 24.55%, 29.85%, 34.2%, and 37.88%, respectively.

Figure 3 Plexiglas's wall section.

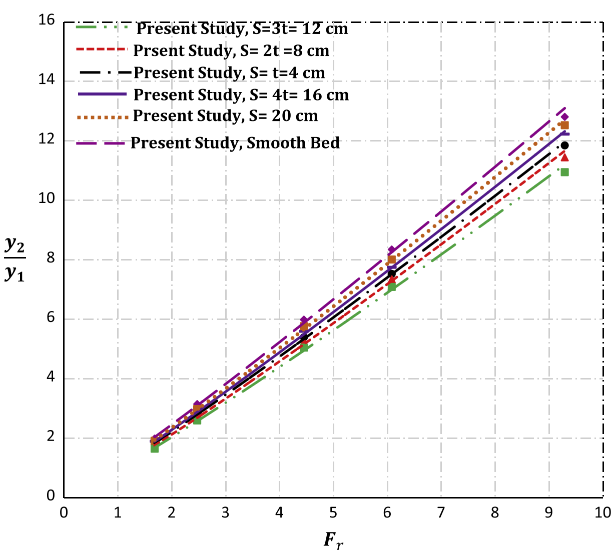

Figure 4 Relation between relative sequent depth y_2/y_1 and Froude number F_r.

A power regression analysis of observed data led to the following formula for optimal spaced rough beds:

$$y_3/y_1 = 0.9247(F_r)^{1.0551} \quad R^2 = 0.98 \tag{5}$$

3.3. Tail water depth of jump

Fig. 7 shows the relation between the initial Froude number and relative tailwater depth of jump (y_t/y_1) at spacing between corrugated beds S = (4, 8, 12, 16 and 20 cm).

One can see that, for the considered flow conditions, at optimal spaced triangular corrugated beds (S = 12 cm), the relative tailwater depth decreases by 2.23%, 6.32%, 9.26%, 13.12% and 15.36% in comparison with that of the smooth bed for F_r = 1.68, 2.47, 4.45, 6.08 and 9.29 respectively. The results indicate that changing the spacing between corrugated

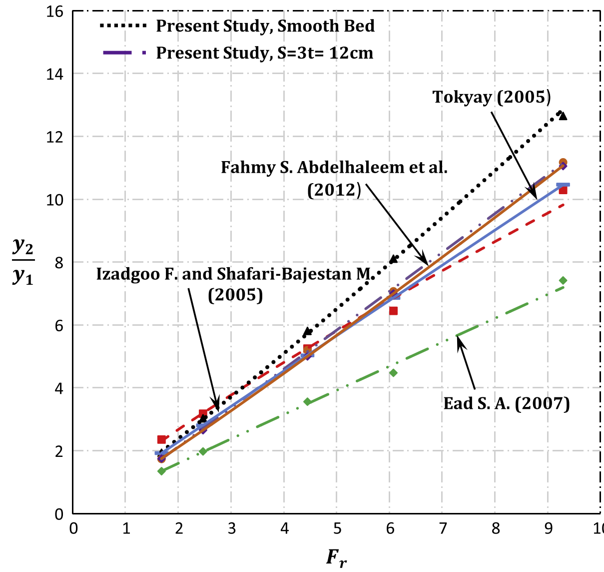

Figure 5 Compassion relationship between (y_2/y_1) and F_r for present study and previous studies.

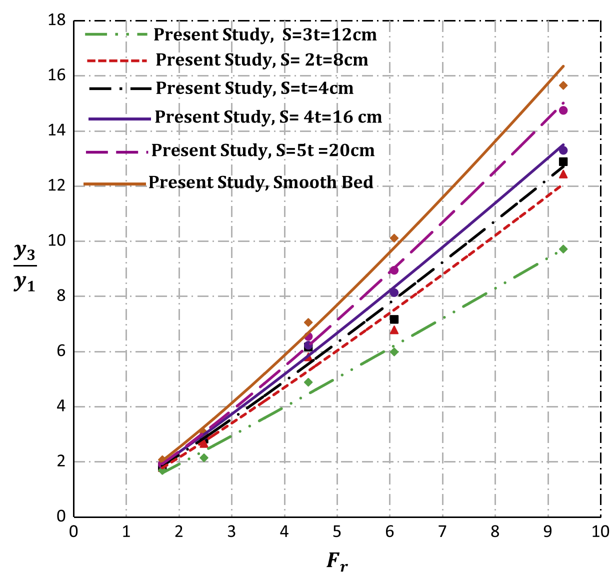

Figure 6 Relationship between relative submerged ratio y_3/y_1 and F_r.

beds has a small influence on the tailwater depth ratio. Out of all trials, the best equation predicting the relative tailwater depth at optimal spaced rough bed can be put in the following form.

$$y_t/y_1 = 1.3921(F_r)^{1.0943} \quad R^2 = 0.99 \tag{6}$$

3.4. Deficit depth ratio

Present research and all previous studies confirm that, the created sequent depth due to jumps over corrugated bed (y_2) is less than sequent depth (y_z^*) for classical jumps (smooth bed), so, in order to show the amount of difference between (y_2) and (y_2^*), a dimensionless index (D) which is defined as:

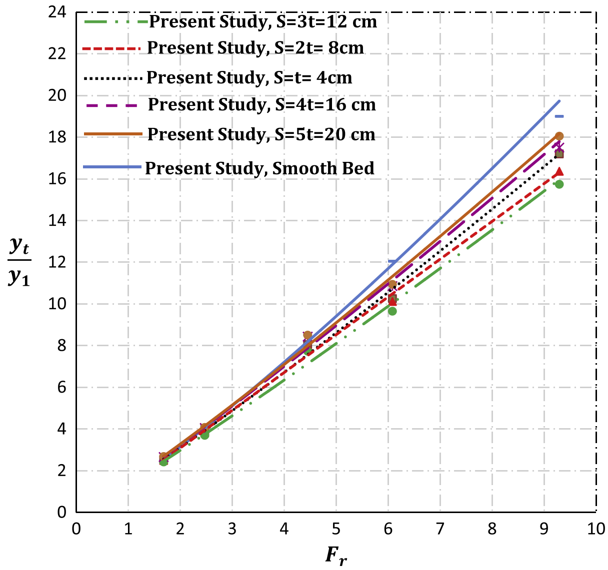

Figure 7 Relation between relative tail-water depth y_2/y_1 and F_r.

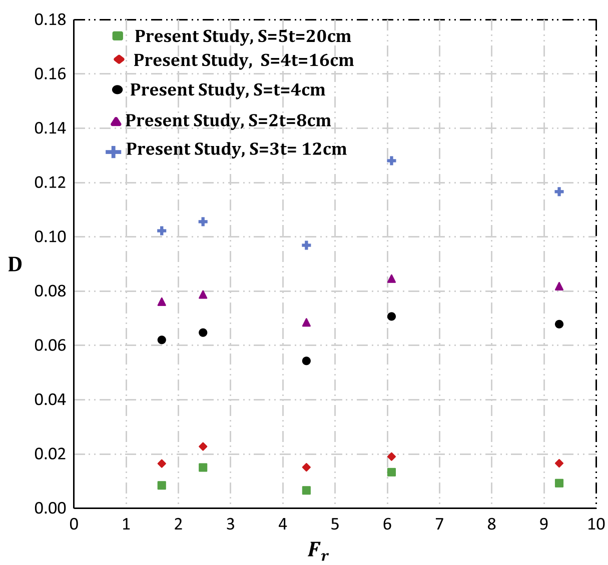

Figure 8 Relation between depth dimensionless index, D and F_r.

$$D = \frac{y_2^* - y_2}{y_2} \tag{7}$$

Dimensionless index (D) is computed for all experimental runs and was plotted against Froude number, as shown in Fig. 8. The results indicate that, D is variable with flow discharge and maximum values of deficit depth ratio are achieved at $S = 3t = 12$ cm. Ead and Rajaratnam [15] used a sequent depth reduction parameter (D), that is, a percentage relative to a smooth bed to evaluate the reduction in the sequent depth that is required to form a jump over a corrugated bed. The results of their experiments indicate a constant value of approximately 0.25. Zhilin and Ashraf [34] confirmed that this parameter is not constant and that its value instead ranges from 0.10 to 0.33 for strip rough bed and from 0.14 to 0.40 for staggered rough bed.

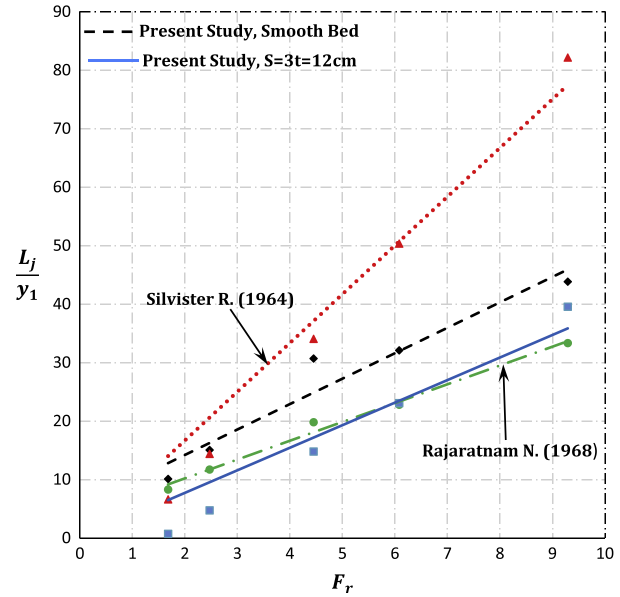

Figure 9 Comparison relation between present study for L_j/y_1 and F_r with previous studies.

3.5. Relative jump length

Fig. 9 shows the comparison between the optimal measured relative jump length (L_j/y_1) of the present study and that of previous studies. From this figure, it is noticed that, the length of jump over spaced corrugated bed is smaller than the length of jump over smooth bed and the length increases as Froude number increases. Also, it can be noticed that, the predicted data agrees well with Rajaratnam [7] for $1.68 \leqslant F_r \leqslant 9.29$ but with Silvester [35] for $F_r \leqslant 2.5$ only. Considering all the trials, the best equation for predicting the relative jump length can be written in the following form:

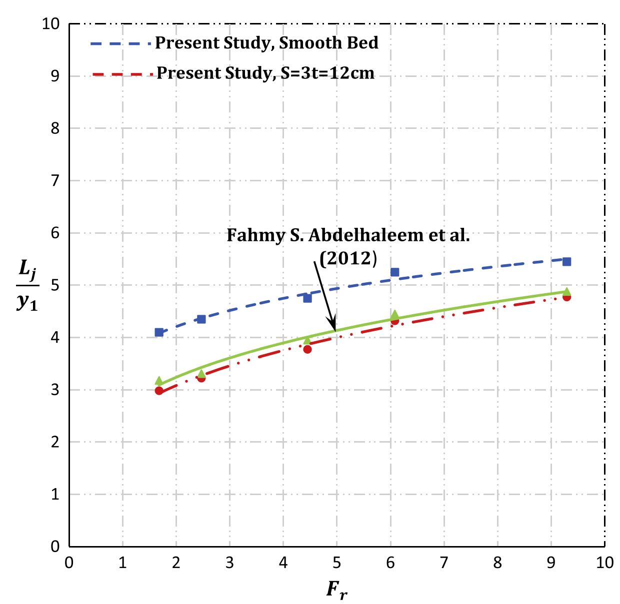

Figure 10 Comparison relation between present study for L_j/y_2 and F_r with previous studies.

$$\frac{L_j}{y_1} = 5.6078(F_r)^{0.8019} \quad R^2 = 0.99 \tag{8}$$

3.6. Jump length ratio

Fig. 10 shows that the relation between the initial Froude number (F_r) and the dimensionless length of the jump (L_j/y_2). From this figure, it is noticed that, the length of hydraulic jump over the spaced corrugated beds is smaller than the length of jump over smooth bed and jump length increases with Froude number increases. It is worth mentioning, it was very difficult to measure the jump length precisely.

At optimal spacing $S = 3t = 12$ cm the length of jump decreases compared with smooth bed by 27.75%, 24.16%, 20.17%, 17.92%, and 15.16% for $F_r = 1.68, 2.47, 4.45, 6.08$, and 9.29 respectively. Fig. 10 demonstrates that the Froude number (F_r) has significantly affected on the jump length. This figure indicates that the obtained values of ($L_j/_z$) for optimal corrugated bed at space 12 cm in the present study are in good agreement with collected data from the statistical analysis of Abdelhaleem et al. [30], although, they studied the characteristics of free hydraulic jump and the present research is related to the characteristics submerged jump. Statistical analysis of the results for (F_r) and L_j provides us with the following equation:

$$L_j = [5.5729(F_r)^{-0.284} y_2] \quad R^2 = 0.98 \tag{9}$$

3.7. Relative roller jump length

The roller jump length (L_r) is the horizontal distance between the toe section of the flow depth $y_1$and the roller end in case of free jump but in submerged jump case it is considered as a horizontal distance from the gate to the roller end. This length can be estimated by a visualization technique, such as with a float to localize the stagnation point. Pietrkowski [36] and Smetana [37] conducted experimental studies to investigate the parameters of classical jump and suggested that the relation between the relative roller length and sequent depth can be written as the following equation:

$$\frac{L_r}{y_1} = \propto \left[\frac{y_2}{y_1 - 1}\right] \tag{10}$$

where "∝" is a coefficient.

Its value was determined by Smetana [37], Citrini [38] and Mavis and Laushey [39] and equal to 6, 5.5 and 5.2 respectively.

Fig. 11 illustrates comparison relation between the initial Froude number F_r and the dimensionless roller length of jump (L_r/y_1) at optimal spaced corrugated bed $S = 3t = 12$ cm with previous studies. From this figure, it is noticed that, generally, the roller length of jump over corrugated bed is smaller than the roller length of jump over smooth bed and with increasing the Froude number values the roller length increases accordingly.

This figure indicates that the obtained values of (L_r/y_1) for optimal corrugated bed at optimal spaced corrugated bed $S = 3t = 12$ cm in the present study are in satisfactory agreement with data from the statistical analysis of Smetana [37], Citrini [38] and Hager and Bremen [40] for $F_r \leqslant 3$. Statistical analysis of the results for (F_r) and (L_r) provides us with the following equation:

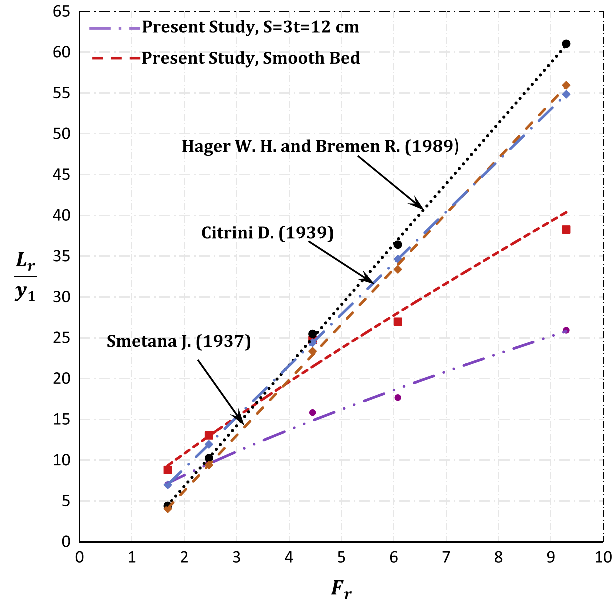

Figure 11 Comparison relation between present study for L_r/y_1 and F_r with previous studies.

$$\frac{L_r}{y_1} = 4.8499(F_r)^{0.7498} \quad R^2 = 0.99 \tag{11}$$

3.8. Jump efficiency

The efficiency of the hydraulic jump (η) can be expressed as $\eta = (E_2/E_1)\%$ where E_1 and E_2 are the energies before and after the jump. Fig. 12 shows the variation of efficiency with initial Froude number, F_r for different spaced corrugated

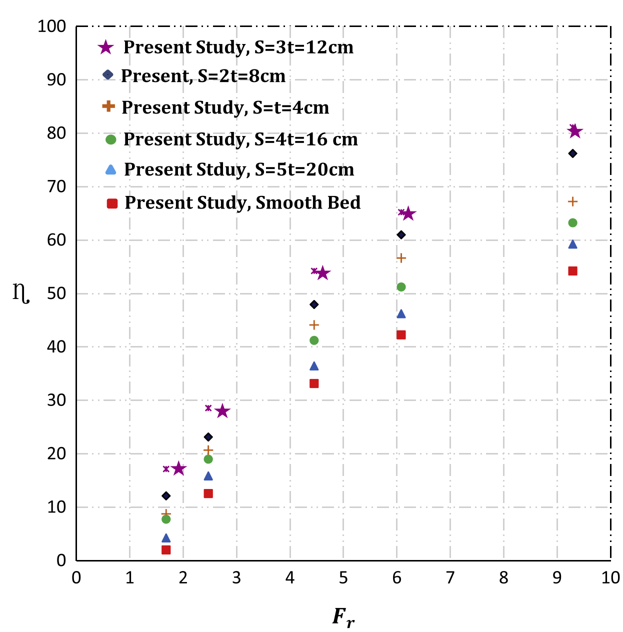

Figure 12 Relation between jump efficiency η and F_r.

bed. It reveals from the figure that roughness effect is clear as all data lie above the smooth bed case, but the effect of roughness density is almost similar for the range used indicating a general increasing trend for increased initial Froude number. The maximum values of jump efficiency occur at spaced corrugated bed $S = 3t = 12$ cm and the efficiency of jump increases compared with smooth bed by 88.34%, 56.02%, 38.85%, 35.21% and 33.14% for $F_r = 1.68$, 2.47, 4.45, 6.08, and 9.29 respectively. Statistical analysis of the results for (F_r) and (η) provides us with the following equation:

$$\eta = 11.882F_r^{0.9188} \quad R^2 = 0.89 \tag{12}$$

3.9. Bed shear stress

One of the main objectives of installed corrugated bed sheets is to increase the bed shear stress and, the sequent water depth and the length of the hydraulic jump thus is reduced. In the present section, the bed shear stress is calculated using the momentum equation as following:

$$F_r = (P_1 - P_2) + (M_1 - M_2) \tag{13}$$

where P_1, P_2, $M1$ and $M2$ are the integrated pressures and momentum fluxes at sections prior and after the hydraulic jump, respectively. Also the shear force index (ε) can be written as:

$$\varepsilon = \frac{F_r}{0.5\gamma y_1^2} \tag{14}$$

where γ is unit weight of water.

The relation between shear force index (ε) and Froude number (F_r) is shown in Fig. 13, it is apparent that, shear force index increases with increase Froude number for all spaces of corrugated bed with varying degrees. One can see that, spaced triangular corrugated bed at $S = 3t = 12$ cm is the best of all spaced corrugated beds. Statistical analysis of the results data of optimal spaced corrugated bed at ($S = 3t$) for the relationship between (ε) and (F_r) provides us with the following equation:

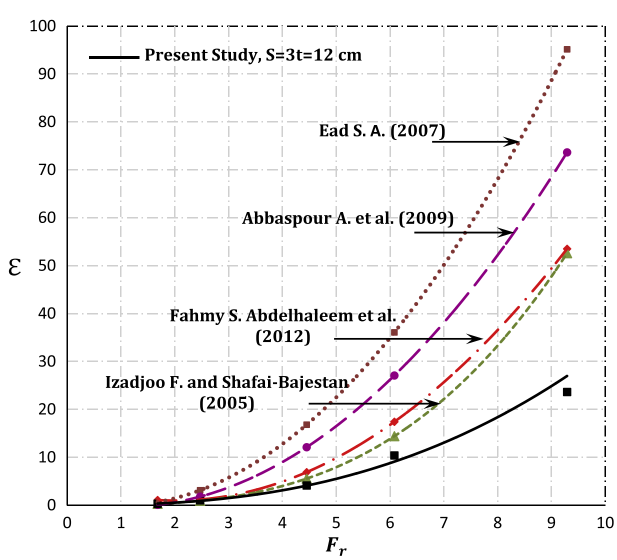

Figure 13 Comparison relation between shear force index and F_r for present research and previous studies.

$$\epsilon = 0.0885F_r^{2.5657} \quad R^2 = 0.96 \tag{15}$$

Fig. 13 presents a comparison relation between the results of current study for optimal spaced corrugated bed and smooth bed with previous studies. This figure indicates that the obtained values of ε for optimal corrugated bed in the present research are in good agreement with those that determined by Izadgoo and Shafai-Bajestan [31], Ead [33], Abbaspour et al. [41] and Abdelhaleem et al. [30] for $F_r \leqslant 3$. With knowledge that they are studied a free jump.

4. Conclusion

The present study investigates the effect of using spaced triangle strip corrugated sheets as a bed roughness material on the main geometric parameters of the submerged hydraulic jump. Preliminary tests over a smooth horizontal bed confirmed the well-known results reported in the literature. The following prominent conclusions can be drawn:

- Corrugated beds always showed better performance than smooth beds channel in enhancing hydraulic jump characteristics by increasing bed shear stress,
- Optimum spaced corrugated bed sheets at $S = 12$-cm, reduce the sequent depth of hydraulic jump and the results agree well with Izadjoo and Shafai-Bajestan (2005), Tokyay (2005) and Abdelhaleem et al. (2012),
- Submergence depth (y_3) and tail water depth (y_t)at downstream reduced by 29.03% and 9.26% respectively at the optimum spaced corrugated bed sheets,
- Optimum spaced corrugated bed sheets reduce the relative jump length of hydraulic jump and the results agree well with Rajaratnam (1968) for $1.68 \leqslant F_r \leqslant 9.29$ and with Silvester (1964) for $F_r \leqslant 4.5$ only,
- The length of jump reduces by 20.03% in comparison with smooth bed and the results of present study agree well with Abdelhaleem et al. (2012),
- The length of roller jump is found to be depended largely on corrugated beds, and the results of present study agree well with Smetana (1937), Citrini (1939) and Hager and Bremen (1989) for $F_r \leqslant 4.5$,
- Corrugated beds confirmed the effectiveness for energy dissipation at downstream hydraulic structures and reduce the cost of the apron,
- All spaced triangular corrugated beds reduce jump characteristics and consequently, increase jump efficiency in comparison with smooth bed case specially at the optimum spacing between corrugated bed sheets $S = 3t = 12$ cm,
- Spaced corrugated bed sheets increase the eddies that were created between bed sheets and consequently increase the bed shear stress,
- The amount of shear stress was found to be a function of Froude number,
- Empirical formulae were fitted to the experimental data where good agreement is obtained.

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Eng. Hossam Mohamed Ali Eng. Hossam has a wide experience in hydraulic applications in the field, covering the different aspects of hydraulic engineering. He has good experience in planning and designing an irrigation and drainage system, topographic survey, river and hydraulic structures studies, executing pump station, different hydraulic structures (such as bridges, culvert, barrage), and flow in pipes. He holds an international diploma in river basins Sciences.

Prof. Mohamed El Gendy *Prof. of Geotechnical and Foundation Engineering Faculty of Engineering Port Said University,* Deputy Dean of Faculty of Engineering for the Environmental Affairs and Community Service, The author of a computer program known ELPLA in conjunction with Prof Manfred Kanye in Nurnberg that consider as his main contribution in the field of geotechnical engineering is an authoring program foundations, published researches in the field of soil mechanics and all types of foundations and supervision on several theses of Master and PhD. Co-author of a collection of books on geotechnical engineering.

Dr. Ahmed Mohamed Hassan Mirdan Assoc. Prof. of irrigation engineering, Faculty of Engineering, Port Said University and manager of unit quality assurance and accreditation project for the continued development and rehabilitation of the adoption and supervision on several theses of Master.

Abdel Azim Mohamed Ali Assoc. Prof. of irrigation and hydraulic engineering, participate in several local and international workshops, publication several scientific researches, participation in the design of major projects in Egypt and responsible for experimental works in laboratories, teaching national scientific courses in Egypt and Africa and published researches in the field of hydraulic field.

Dr. Fahmy Salah Fahmy Abdel Haleem He has a broad experience, covering the different aspects of hydraulic engineering; his professional experience in the sphere of hydrographic, topographic and bathymetric survey, producing surveys maps, river and hydraulic structures studies, executing power plants, barrages studies, teaching national scientific courses in Egypt and Africa, published researches in the field of specialization, supervising master of science and doctoral researchers and technical report writing in both English and Arabic languages.