AUT Journal of Civil Engineering

AUT J. Civil Eng., 4(3) (2020) 349-356
DOI: 10.22060/ajce.2019.16427.5586

The S-jump's Characteristics in the Rough Sudden Expanding Stilling Basin

R. Daneshfaraz[1*], M. Majedi Asl[2], R. Mirzaee [3], A. Ghaderi[4]

[1] Professor, Department of Civil Engineering, Faculty of Engineering, University of Maragheh, Maragheh, East Azerbaijan, Iran.
[2] Assistant Professor, Department of Civil Engineering, Faculty of Engineering, University of Maragheh, Maragheh, East Azerbaijan, Iran.
[3] M.Sc. Student, Department of Civil Engineering, Faculty of Engineering, University of Maragheh, Maragheh, East Azerbaijan, Iran.
[4] Ph.D. Student, Department of Civil Engineering, Faculty of Engineering, University of Zanjan, Zanjan, Iran.

ABSTRACT: One way to dissipate energy is to use sudden expansion stilling basin structures downstream of spillway, gates and chute. The present study is aimed to study influences of shear stress caused by a rough bed on S-jump's characteristics in an expanding stilling basin. Experiments were performed in a horizontal laboratory flume with a rectangular cross-section, a Plexiglas wall and floor with an expanding ratio of 0.33, a Froude number range of 5.38 to 10.78. The results showed that the shear stress of the rough bed in the expanded stilling basin was more than 13.5 times the shear stress of the prismatic stilling basin with a smooth bed. Secondary depth and the length of the s-jump on the rough bed have reduced to 20% and 16%, respectively. Also S- jump with rough beds reduces the secondary depth by about 58.5% compared to classical hydraulic jump. Increased shear stress has a marginal impact on jump efficiency, so that the effect of expanding on jump efficiency is greater than the effect of increased shear stress. Expanding stilling basins with a smooth and rough bed are moderate compared to prismatic basin. It can and increase the jump efficiency for smooth and rough bed by 23.5 and 28.7%, respectively.

Review History:

Received: 2019-05-26
Revised: 2019-07-27
Accepted: 2019-07-29
Available Online: 2019-08-03

Keywords:

Shear stress
S-jump
Expanding stilling basin
Rough Bed
Energy dissipation

1.INTRODUCTION

Dissipation of the energy of flow is the primary issue of spillways. In this way, using stepped spillway, ski jump buckets and stilling basin at the toe of spillways have been suggested [1]. The stilling basins in the downstream of the supercritical flow producer, with the possibility of forming a hydraulic jump, dissipate a large part of the stream's destructive kinetic energy, and prevents downstream destruction and erosion. The most important parameters in the design of the stilling basin are the width, length, and height of the walls, as well as the bed elevation [2-3]. These factors depend on the characteristics of the hydraulic jump and tail water depth. In lower tailwater depth of stilling basin and because of some specific project's topographic and economic restriction, it is not possible to excavate the stilling basin to stabilize the jump. The use of cross-sectional expansion can be one of the ways to ensure the creation and stabilization of the jump in the stilling basin. In expanding the stilling basin, in addition to jump stabilization, asymmetric flow is created.

Depending on the tailwater depth, three jumps can be formed. In lower tailwater, the toe of the jump is lower than the point at which the cross-wave hits the channel's wall (point A in Fig. 1) and an R-jump will be formed. By increasing the depth, the jump occurs between the expansion section and point (A) in Fig. 1, and it is a S-jump. This jump is more like an asymmetrical and oscillating jet and forms without surface rollers. By increasing the tailwater, the toe of the jump is higher than the junction section and a T-jump will be formed. This jump can be symmetric or asymmetric, depending on how far the toe of the jump can form from the junction [4].

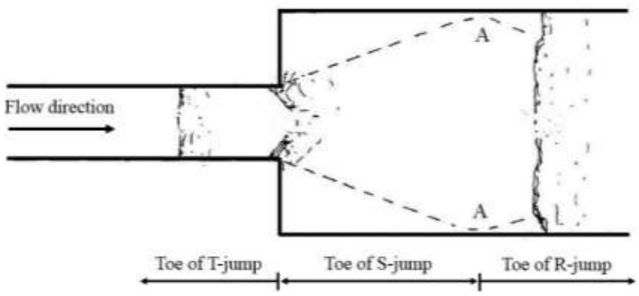

Fig. 1. Classification of hydraulic jumps in a prismatic channel with sudden expansion [5].

An S-jump is usually discussed as a phenomenon with very different flow conditions, which are difficult to precisely calculate because of discrete flow properties [6]. Unny [7], Herbrand [6], Alhamid [8], and Matin et al. [9] carried out studies in this field to predict the depth ratio of S-jump. Unny [7] conducted his studies by considering a turbulent theory with an expansion ratio of 0.5. Herbrand [6], in addition to presenting a simple relation to the depth of the S-jump, stated that a S-jump without appurtenances of the controller tended to be unstable and asymmetric and could damage the stilling basin. Alhamid [8] also showed that the

*Corresponding author's email:daneshfaraz@maragheh.ac.ir

S-jump compared with the classic jump in the prismatic canal increases the efficiency and jump length. Matin et al. [9] also presented a correlation for the ratio of the depths of the S-jump by determining the modified Froude number in the Belanger equation. The effect of a sill with a different height and location on the characteristics of S-jump in symmetric and asymmetric sudden expansion was investigated by Zare and Doering [10]. Since the formation of a hydraulic jump on a smooth bed on its entire length in stilling basins is not cost-effective, in practice, measures, such as the use of chute blocks, baffle blocks, and the end still, are considered in the stilling basin [11]. The main purpose of these arrangements is to reduce the length of the jump and the dimensions of the stilling basin [12]. Because the baffle blocks are directly in front of the flow inlet jet, high flow rates can cause corrosion and damage due to erosion [13, 14]. If the jump controller elements are in such a way that their crests are equal to upstream and downstream bed of stilling basin, in addition to improving the characteristics of the jump and reducing the size of the stilling basin, it can also be resistant to cavitation. The jump formed on such a bed is called a hydraulic jump on a rough bed.

Other studies on a hydraulic jump with a rough bed was carried out by Rajaratnam [15]. Subsequently, Hughes and Flack [16], Alhamid [8], Ead and Rajaratnam [17], Tokyay [18] and Hassanpour et al. [19] carried out studies in which the results showed that the height, shape, and density of the roughness element has an effect on hydraulic jump characteristics. Aboulatta et al. [20] examined the characteristics of the hydraulic jump on two types of roughness, showing that T-shaped elements with a density of 8 compared with rectangular elements with a density of 10 have more favorable results. Samadi Boroujeni et al. [21] showed that the length and secondary depth of the hydraulic jump on the triangular corrugated bed decreases 54.7% and 25%, respectively. Parsamehr et al. [22] also investigated experimentally the characteristics of the hydraulic jump on an adverse slope with a rough bed. They showed that the secondary depth and jump length decrease with an increasing height of the roughness and an adverse slope. For the first time in 2013, the effect of a rough bed on S-jump characteristics was investigated for four expanding ratios and a range of Froude numbers from 2 to 10 by Neisi and Shafai Bajestan [23]. The results showed that the secondary depth of the S-jump on the bed is reduced approximately 53% compared with a secondary classical jump on smooth bed. Daneshfaraz et al. [24, 25], by studying the s-jump in different expanding ratios on roughness bed, showed that increasing roughness element height in addition to decreasing more than 12 to 20 percent jump length, causes educing secondary s-jump depth 20 to 30.4 percent on roughness bed in comparison to smooth bed.

According to literature reviews, it was observed that the S-jump, in comparison with the classic jump in the prismatic channel, increases the jump length and the maximum created jump length occurs with a low expanding ratio. On the other hand, bed roughness can reduce the length of the jump and also previous studies show that the shape of the roughness blocks are effective on the length of jump. The purpose of this study was to investigate the effect of shear stress due to roughening of the bed by non-continuous trapezoidal elements on the S-jump characteristics with an expanding ratio of 0.33 compared with smooth bed and previous research.

2. METHODS AND MATERIALS

2-1- Experimental Set up

The experiments were carried out in a laboratory flume with transparent and oblong Plexiglas and rectangular section with lengths, widths, and heights of 5, 0.3 and 0.45 meters, and a zero-sloped bed in the Hydraulic Laboratory of Maragheh University. To create a super-critical flow, a sluice gate with an opening height of 1.7 cm was placed half a meter from the beginning of the flume. At the upstream side of the gate, the flume height was increased to 25 cm to create a reservoir with a height of 65 centimeters. To create a symmetrical sudden expansion with an expansion ratio of 0.33, glass boxes, with widths, lengths, and heights of 10, 50, and 20 cm-2 were used on both sides of the flume before and after the gate. Also, to roughening of the bed, the trapezoidal elements are distributed in a staggered 2-3-2 manner, and to the longitudinal and transverse intervals of the elements of the same size of 6 cm in a stilling basin with a length of 120 cm are used. According to Mohammad Ali's research [27], the distance between the first rows of roughness elements were placed at the height of their feet from the toe of jump (which is the same as the section change region). Fig. 2 illustrates a schematic of the

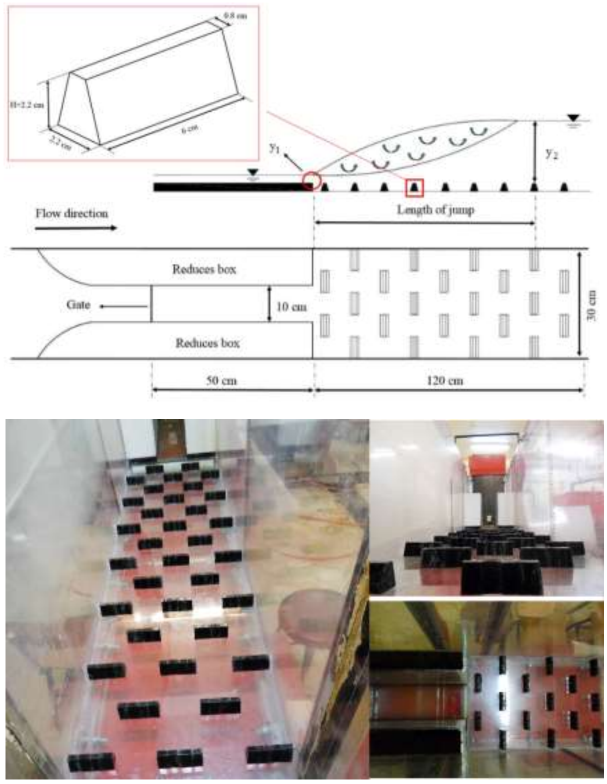

Fig. 2. Schematic of the laboratory model

Fig. 3. View of S-jump on the rough bed

Table 1. Range of Measured Variables

Bed	q(m^3/s.m)	Fr_1	y_1(cm)	V_1(m/s)	y_2(m)	L_j(m)
Smooth	0.0250-0.0416	5.38-10.78	0.0115-0.0130	1.92-3.63	0.052-0.082	0.640-1.110
Rough	0.0252-0.0416	5.40-10.80	0.0115-0.0130	1.93-3.63	0.042-0.065	0.555-0.925

experimental model in the present study. After the stability of flow conditions, the initial and secondary depths and the length of the hydraulic jump were measured. The initial and secondary depths of the jump were measured using two tools. First, water height measurement during experiments was carried out using Ultrasonic Digital Measuring Instruments. These instruments have a precision of 140 data per second. Recording a large number of data per second makes it possible to understand flow fluctuations. Then, using a point gauge with a precision of 1 mm at five points of the cross-section, the flow depth was measured and the mean values obtained from the two methods after comparison were considered. The method is inspired by Torabi et al. in 2015 which used different vertical point gauges in the desired cross-section to capture water surface fluctuation to find the exact profile [28]. The length of the jump was measured with a 1 mm precision ruler. Fig. 3 shows the S-jump view on the rough bed. The range of measured variables is also presented in Table 1.

2-2- Dimensional Analysis

The characteristics of the S-jump on a rough bed are influenced by fluid characteristics, hydraulic conditions, and physical characteristics of the model. ρ mass density, v_1 jump velocity, μ dynamic shear force, ε shear stress coefficient, g gravity acceleration, b_1 upstream channel width, b_2 downstream channel width, y_1 initial depth of jump, y_2 secondary depth of jump, H height of roughness elements, L_j jump length, I Percentage of roughness and E_L, E_1 and E_2 are respectively, energy loss energy upstream and energy downstream, that can be considered as the most important parameters in the present study (Eq. 1).

$$f(\rho, v_1, \mu, g, b_1, b_2, y_1, y_2, H, L_j, I, \varepsilon, E_L, E_1, E_2) = 0 \quad (1)$$

By applying the π -Buckingham theory and choosing μ, v_1, and y_1 as repeating parameters and after simplification, the dimensionless quantities were obtained by the following equation (Eq. 2).

$$f\left(Fr_1, \mathrm{Re}_1, I, \varepsilon, D_s = \frac{y_2}{y_1}, \lambda_s = \frac{L_j}{y_1}, \alpha = \frac{H}{y_1}, B = \frac{b_1}{b_2}, \eta = \frac{E_L}{E_1}, \frac{E_2}{E_1}\right) = 0 \quad (2)$$

In this equation, Fr_1, Re_1, Ds, λ_s, α, B, η are respectively the Froude number in the toe of the jump, the Reynolds number in the toe of jump, the ratio of the S-jump depth, the relative length of the S-jump, the relative height of the roughness elements, the ratio of the expanding section, and the jump efficiency. Since the density of the roughness element and the height of the gate opening are constant, we can neglect the effect of I and α. On the other hand, as the maximum length of the jump length in previous studies happens at a low expanding ratio, an expanding ratio of 0.33 is chosen for the experiments, and it is possible to neglect the effect of B that is constant. Also, the Reynolds number range is from 100,000 to 166,666 in this study.

The flow is completely turbulent and the effect of viscosity is negligible, so choosing D_s, λ_s, ε, η as the dependent parameters, Eq. 2 is determined as Eq. 3.

$$f(Fr_1) = \varepsilon, D_s, \lambda_s, \eta \quad (3)$$

in the present study, the minimum and maximum discharge by the pump was 2.5 lit/s and 4.7 lit/s, respectively. In the above relation, the range of the Froude number is from 5.38 to 10.78.

2-3- Material and Method

By applying the momentum equation in the sudden

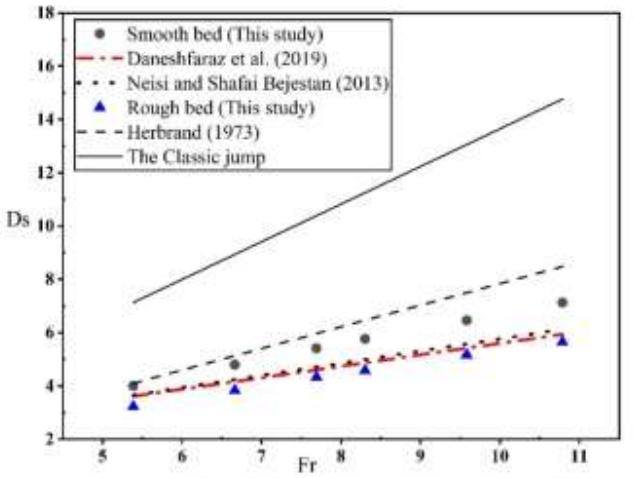

Fig. 4. The ratio of S-jump depths versus the Froude number

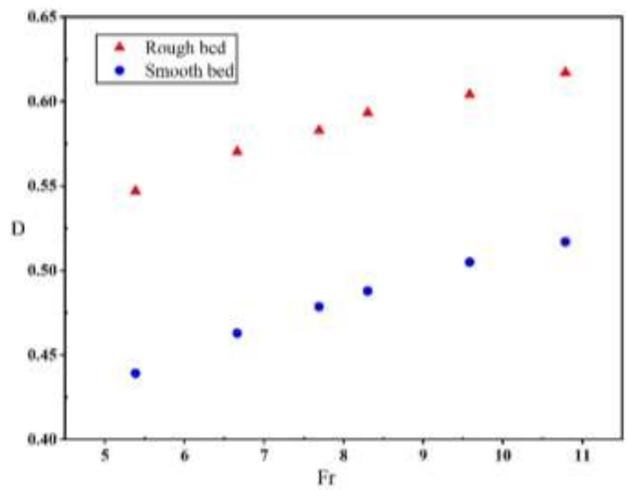

Fig. 6. Changes in parameters relative to the secondary depth reduction versus the Froude number

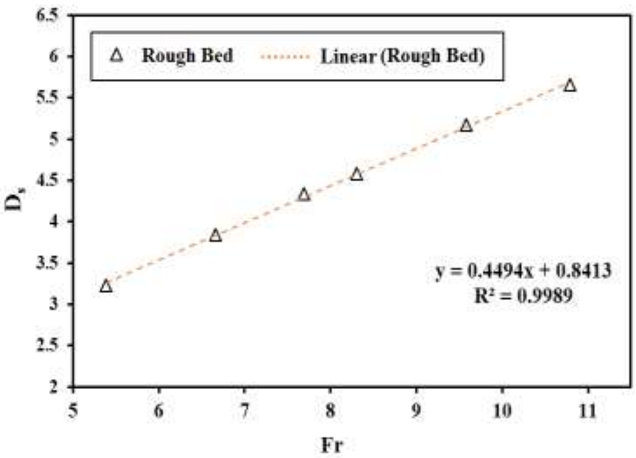

Fig. 5. Linear fit of the ratio of the depth of the S-jump on the rough bed

expanding rough section and selecting F_τ as the total shear forces in the length of the jump, the Eq. 4 can be written as:

$$F_\tau = (M_1 - M_2) + (F_1 - F_2) + F_e \quad (4)$$

In the above equation, F_1 and F_2 are the compressive forces before and after the jump, M_1 and M_2 the momentum before and after the jump, and $F_e = 0.5\,\gamma\,(b_2 - b_1)\,y_1^2$ the force of pressure on the wall expanding section and γ the specific gravity of the water.

The coefficient of shear stress in the smooth and rough bed is calculable using Eq. 5 [10].

$$\varepsilon = \frac{F_\tau}{0.5\gamma y_1^2} \quad (5)$$

3.RESULTS AND DISCUSSION

3-1- The depth ratio

According to dimensional analysis, the ratio of the depths of the S-jump is a function of the initial Froude number of the flow. Accordingly, the depth ratio for the rough and smooth bed of the present research and previous research is shown in Fig. 4 relative to the Froude number. According to Fig. 4, the ratio of the depth of the S-jump increases linearly with increasing Froude numbers. Also, by comparing the depth of the jump on the rough bed of the present study with the smooth bed and other studies it is deduced that due to the effect of bed roughness and shear stress increase, compared with the smooth bed and pediatric research of Herbrand [6], Neisi and Shafai Bajestan [23] and Daneshfarz et al. [24]. The secondary depth of the S-jump on the rough bed of the present study decreased 20% compared with the smooth bed.

The linear fit of the S-jump depth on the rough bed of the present study was obtained in Fig. 5 with a coefficient of 0.998 as the Eq. 6:

$$D_s = 0.4494 Fr_1 + 0.8413 \quad (6)$$

The dimensionless depth parameter to compare the secondary depth of S-jump on the smooth and rough bed with the secondary depth of classical hydraulic jump according to Ead and Rajaratnam [17], is shown as Eq. 7 and the results are shown in Fig. 6.

$$D = \frac{y_2^* - y_2}{y_2^*} \quad (7)$$

In the above equation, y_2^* is the secondary depth of the classic jump in the prismatic stilling basin.

In Fig. 6 it can be seen that for both smooth and rough beds by increasing the Froude number the parameter for decreasing secondary depth has increased, and this increase is shown in the rough bed due to increased shear stress. The average secondary depth reduction parameter for all Froude values for smooth and rough beds are 48% and 58.5%, respectively, which means that expanding stilling basins with rough beds in the present study at an expanding ratio of 0.33 reduces 58.5% of the secondary depth.

3-2- Relative length of the jump

The length of the jump is one of the important parameters

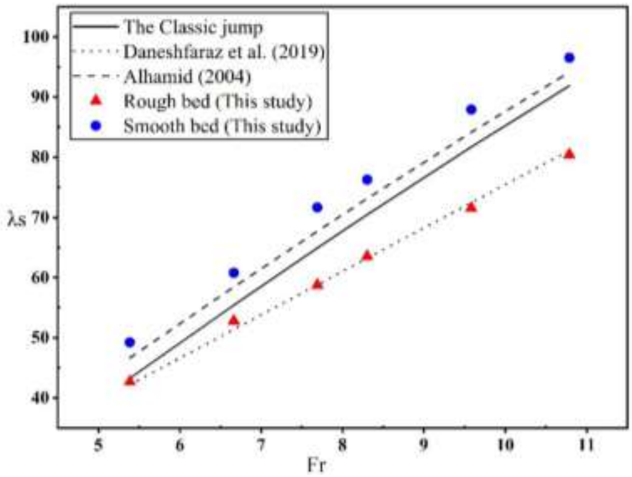

Fig. 7. Changes in the relative length of the jump versus Froude numbers

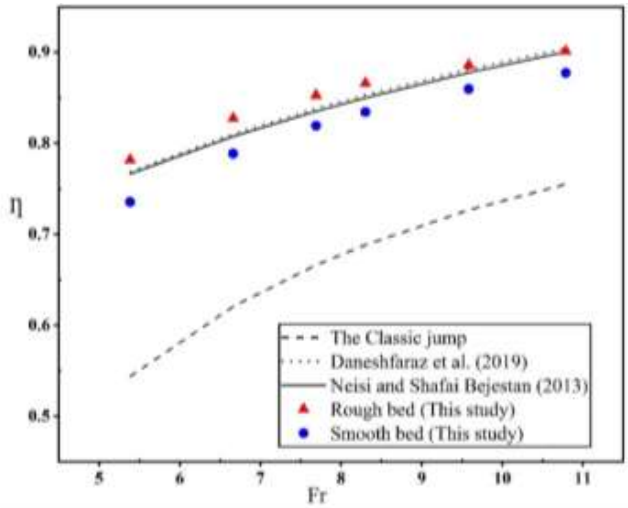

Fig. 9. Changes in jump efficiency versus the Froude number

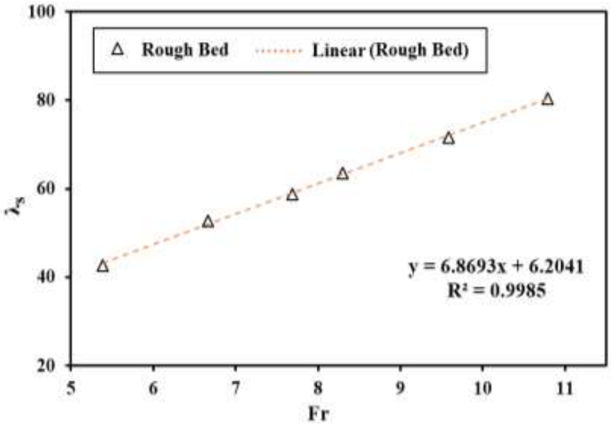

Fig. 8. Linear fit of the relative length of the s-jump on a rough bed

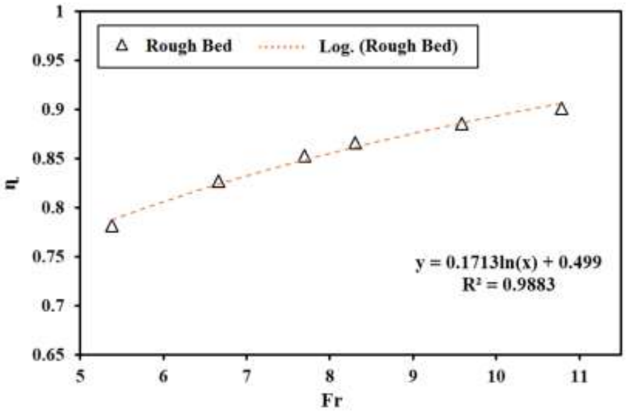

Fig. 10. Logarithmic fitting of the s-jump on a rough bed

in the economic design of the stilling basin. Therefore, it's important to investigate it. According to the dimensional analysis, the relative length of the S-jump on the rough and smooth bed of the present study and the previous studies in Fig. 7 are shown versus the Froude number. According to Fig. 7, it is observed that the S-jump length in a sudden expanding stilling basin with a smooth bed is increased compared with the classical jump length and the amount of its length is close to the relative length of the jump in Alhamid's studies [8]. Also, increasing the shear stress of the bed reduces the length of the S-jump on a rough bed compared with the smooth bed. The length of the S-jump decreases so that for all Froude number values, the S-jump length on the rough bed is less than its corresponding amounts in a classic jump. In addition, as the S-jump asymmetry on a smooth bed and the collision of the jet with the channel wall, which can lead to gradual wall erosion, increasing the shear stress reduces the intensity of the inflow jet into the flume wall and it makes the flow take on a direct path (Fig. 3). It is also concluded that the relative length of the jump on the rough bed of the present study is less than what has been seen in other research. The average reduction in the length of the S-jump on the rough bed compared with the smooth bed and classic jump was 16 and 8.4%, respectively.

Considering experimental values and linear fit, the relative length of the S-jump on the rough bed of the present study with a coefficient of 0.998 in Fig. 8 was obtained as follows:

$$\lambda_s = 6.8693 Fr_1 + 6.2041 \quad (8)$$

3-3- Jump Efficiency

The specific energy difference before and after the jump is called the energy loss, and the relative energy loss or jump efficiency is expressed as the ratio of energy loss to specific energy before the jump. The jump efficiency in the present study is calculated for a smooth bed and is compared with its corresponding amounts in a classical jump and other studies that is shown versus the Froude number in Fig. 9. Regarding Fig. 9, it can be seen that an increasing jump efficiency graph with increasing Froude numbers for all research shows a lower slope. Also, the s-jump on the rough bed of the present study compared with the smooth bed, on average has increased efficiency to 4%, which means that in the expanding stilling basin with a rough bed, the effect of expanding on jump

Table 2. Average values of the efficiency increase in a non-prismatic channel with a smooth and rough bed compared with a prismatic channel

	G (%)
Smooth Bed	23.5
Rough Bed	28.7
Daneshfaraz et al. (2019)	26.7
Neisi and Shafai Bajestan (2013)	26.6

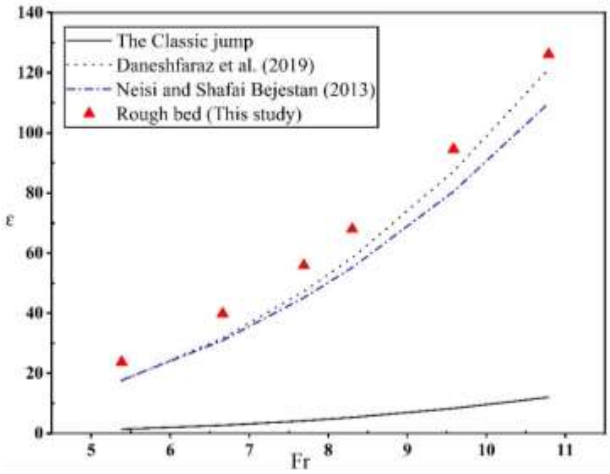

Fig. 11. Changes in shear stress versus Froude number

efficiency is greater than the effect of increasing shear stress.

Also, for a better comparison of the values of Fig. 10, the increase in the efficiency of the s-jump on a flat and rough bed compared with the classical jump in a prismatic channel with a smooth bed was determined based on Eq. 9 and its mean values are given in Table 2.

$$G(\%) = \frac{\eta - \eta^*}{\eta^*} \times 100 \tag{9}$$

In the above equation, η represents the s-jump efficiency on a rough bed and η^* the classical jump efficiency in a prismatic channel.

According to the values of Table 2, expanding stilling basins with an expansion of 0.33 with smooth and rough bed are moderate compared with the prismatic basin and increase the jump efficiency 23.5 and 28.7%, respectively. The present study, with the rough bed, as mentioned above, has a near or greater efficiency value than previous research.

Logarithmically, the efficiency of the s-jump on the rough bed of the present study, as shown in Fig. 10, was found in Eq. 10 to have a coefficient of 0.9883.

$$\eta = 0.1713\, Ln\, Fr_1 + 0.499 \tag{10}$$

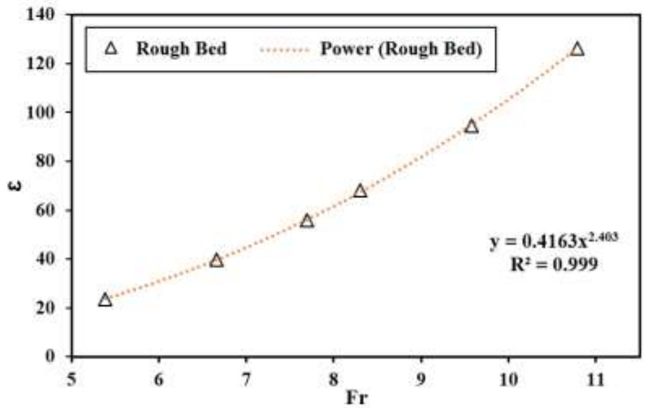

Fig. 12. Power regression of shear stress coefficient

3-4- Coefficient of shear stress

Any change in the channel bed or stilling basin that increases the flow turbulence and decreases the secondary depth and jump length can change the bed's shear stress too. Therefore, the study of shear stress changes in the bed has great importance. In the present study, the shear stress coefficient was calculated using Eq. 5. Fig. 11 shows the shear stress coefficients of the present study and other research compared with the Froude number. It is observed that the process of increasing the shear stress of the bed is similar for all studies, and exponentially increasing Froude numbers. For low Froude numbers, the shear stress coefficient of all studies and the present research is close to each other, with increasing Froude numbers. The shear stress of the bed in an S-jump on a rough bed compared with the shear stresses of the classic jump in the prismatic channel also increased from 11.5 to 17.8, and on average increased 13.5 times. The increase in shear stress due to the formation of rotational flows behind the roughness elements and by increasing the Froude number behind multiple elements causes the shear stress to increase with greater intensity, and therefore, increases flow turbulence. Also, the shear stress coefficients of this study are more than those of Neisi and Shafai Bajestan [23] and Daneshfarz et al. [24] studies. The reason for the difference between the values of the shear stress coefficient in this study and other research could be the difference in the density of roughness elements, and the height of the elements, as well as the shape and type of the rough bed.

The exponents' relationship between the shear stress coefficient and the Froude number of the flow for the present study is illustrated by data regression in Fig. 12 .and Eq. 11 is calculated with a determination coefficient of (0.999).

$$\varepsilon = 0.416 Fr_1^{\,2.403} \tag{11}$$

4- Conclusion

In this research, the effect of shear stress due to roughening of the bed by non-continuous trapezoidal elements on the S-jump characteristics with an expanding ratio of 0.33 was investigated. The results are as follows:

1- The shear stress of the rough bed in the expanding stilling basin is 13.5 times higher than that of the bed's shear stress in the smooth bed.

2- Increasing shear stress causes a 20% reduction in the secondary depth of the s-jump on a rough bed compared with a smooth bed.

3- Since the expanded section with a smooth bed increases the length of the s-jump compared with the classic jump, the increase in shear stress reduces the length of the classic jump to 8.4 %, in addition to reducing the length of the s-jump by 16% compared with a smooth bed.

4- Increased shear stress has little impact on jump efficiency. A sudden expanding stilling basin on the rough bed in comparison to classic jumps in prismatic basins causes more than 28% of jump efficiency.

5- Due to the absence of symmetry in an s- jump on a smooth bed and the collision of the jets entering the channel wall, these jets can gradually erode the wall; the increase in shear stress leads the flow through the direct path and decreases the intensity of the collision of the water jets with the flume wall.

6- Since a hydraulic jump in the expanding rough stilling basin compared with the jump of prismatic stilling basins has 58.5% less secondary depth and 8.4% less jump length, it can be a suitable alternative for a standard basin.

5- NOMENCLATURE

E_1 Specific energy in upstream of jump (m)
E_2 Specific energy in downstream of jump (m)
E_L Energy loss (m)
b_1 Upstream width of channel (m)
b_2 Downstream width of channel (m)
y_1 Initial depths of jump (m)
y_2 Secondary depths of jump (m)
y^* Secondary depth of jump derived from Belanger equation (m)
L_j Jump length (m)
H Height of roughness element (m)
D Dimensionless depth deficit parameter(-)
F_{r1} Initial Froude number (-)
F_1 Pressure forces before jump (kN)
F_2 Pressure forces after jump (kN)
F_e Pressure force on expansion side wall (kN)
F_τ Shear forces along jump (kN)
M_1 Momentum force before jump (kN)
M_2 Momentum force after jump (kN)
v_1 Velocity at toe of jump (m/s)
g Gravitational acceleration (m/s^2)
μ dynamic viscosity (Pa s)
γ Specific weight of water (kN/m^3)
ρ Mass density of water (kg/m3)
B divergence ratios (-)
D_s Depth ratio of S- jump (-)
I Density of roughness elements (-)
λ_s Relative length of the S- jump (-)
ε Shear stress coefficient (-)
η Jump efficiency (-)
α Relative height of the roughness elements (-)
R_e Reynolds number (-)

6- References

[1] P. Parsaie, A.H. Haghiabi. Evaluation of energy dissipation on stepped spillway using evolutionary computing. Applied Water Science, 9(6) (2019) 144.

[2] R. Daneshfaraz, H. Sadeghi, A. Rezazadeh Joudi, J. Abraham, Experimental Investigation of Hydraulic Jump Characteristics in Contraction and Expansions. Sigma: Journal of Engineering & Natural Sciences/Mühendislik ve Fen Bilimleri Dergisi, 35(1) (2017).

[3] S. Sadeghfam, A.A. Akhtari, R. Daneshfaraz, G Tayfur, Experimental investigation of screens as energy dissipaters in submerged hydraulic jump. Turkish Journal of Engineering and Environmental Sciences, 38(2) (2015) 126-138.

[4] N. Rajaratnam, K. Subramanya, Hydraulic jumps below abrupt symmetrical expansions. Journal of the Hydraulics Division, 94(2) (1968) 481-504.

[5] R. Bremen, Expanding stilling basin. Communication 3. Laboratoire de Con-structions Hydrauliques, EPFL-Lausanne. 1990.

[6] K. Herbrand, The spatial hydraulic jump. Journal of Hydraulic Research, 11(3) (1973) 205-218.

[7] T. E. Unny, The spatial hydraulic jump. Proc. 10th Congress of IAHR, London, (1963) 32–42.

[8] A. A. Alhamid, S-jump characteristics on sloping basins. Journal of Hydraulic research, 42(6) (2004) 657-662.

[9] M. A. Matin, M. R. Hasan, M. A. Islam, Experiment on hydraulic jump in sudden expansion in a sloping rectangular channel. Department of Water Resources Engineering, Bangladesh University of Engineering and Technology, Dhaka, 1000 (2008) 65-77.

[10] H. K. Zare, J. C. Doering, Forced hydraulic jumps below abrupt expansions. Journal of Hydraulic Engineering, 137(8) (2010) 825-835.

[11] H. Zahabi, M. Torabi, E. Alamatian, M. Bahiraei, M. Goodarzi, Effects of Geometry and Hydraulic Characteristics of Shallow Reservoirs on Sediment Entrapment. Water, 10(12) (2018) 1725.

[12] H. Zahabi, M. Torabi, E. Alamatian, M. Bahiraei, M. Goodarzi, Effects of Geometry and Hydraulic Characteristics of Shallow Reservoirs on Sediment Entrapment. Water, 10(12) (2018) 1725.

[13] M. Torabi, A. Hamedi, E.Alamatian, H.Zahabi, The effect of geometry parameters and flow characteristics on erosion and sedimentation in channels junction using finite volume method. (2019)arXiv preprint arXiv:1906.10102. DOI: 10.31033/ijemr.9.2.14

[14] D. Hosseini, M. Torabi, M.A.Moghadam, Preference assessment of energy and momentum equations over 2D-SKM method in compound channels. Journal of Water Resource Engineering and Management, 6(1) (2019) 24-34.

[15] N. Rajaratnam, Hydraulic jump on rough bed. Transaction of the Engineering Institute of Canada, 11(A-2) (1968) 1-8.

[16] W. C. Hughes, J. E. Flack, Hydraulic jump properties over a rough bed. Journal of Hydraulic engineering, 110(12) (1984) 1755-1771.

[17] S. A. Ead, N. Rajaratnam, Hydraulic jumps on corrugated beds. Journal of Hydraulic Engineering, 128(7) (2002) 656-663.

[18] N.D. Tokyay, Effect of channel bed corrugations on hydraulic jumps. Impacts of Global Climate Change Conference Proceeding Paper, EWRI, Anchorage, Alaska, USA, (2005) 408-416.

[19] N. Hassanpour, A. Hosseinzadeh Dalir, D. Farsadizadeh, C. Gualtieri, An experimental study of hydraulic jump in a gradually expanding rectangular stilling basin with roughened bed. Water, 9(12) (2017) 945.

[20] N. Aboulatta, G. Ezizah, N. Yousif, S. Fathy, Design of stilling basins using artificial roughness. International journal of civil and environmental engineering, 3(2) (2011) 65-71.

[21] H. Samadi-Boroujeni, M. Ghazali, B. Gorbani, R. F. Nafchi, Effect of triangular corrugated beds on the hydraulic jump characteristics. Canadian Journal of Civil Engineering, 40(9) (2013) 841-847.

[22] P. Parsamehr, D. Farsadizadeh, A. HosseinzadehDalir, A. Abbaspour, M. J. Nasr Esfahani, Characteristics of hydraulic jump on rough bed with adverse slope. ISH Journal of Hydraulic Engineering, 23(3) (2017) 301-307.

[23] K. Neisi, M. Shafai Bajestan, Characteristics of S-jump on Roughened Bed Stilling Basin. Journal of Water Sciences Research, 5(2) (2013) 25-34.

[24] R. Daneshfaraz, M. Majedi Asl, R. Mirzaeereza, Experimental study of expanding effect and sand-roughened bed on hydraulic jump characteristics. Iranian Journal of Soil and Water Research, (In Press) (In Persian) (2019), DOI: 10.22059/ijswr.2018.261923.667968

[25] R. Daneshfaraz, M. Majediasl, R. Mirzaee, P. Parsamehr, Experimental study of the roughness bed with non-continuous trapezoidal elements on S-jump characteristics in the non-prismatic rectangular channel. Sharif Journal of Civil Engineering, (2019) (In Press). DOI: 10.24200/j30.2018.51630.2423

[26] A.A, Alhamid, Effective roughness on horizontal rectangular stilling basin. Transaction on Ecology and the Environment, 8 1994 39-46.

[27] H. S. Mohammad Ali, Effect of roughened-bed stilling basin on length of rectangular hydraulic jump. Journal of Hydraulic Engineering, 117(1) (1991) 83-93.

[28] M. A. Torabi, M. Shafieefar, An experimental investigation on the stability of foundation of composite vertical breakwaters. Journal of Marine Science and Application, 14(2) (2015) 175-182.

HOW TO CITE THIS ARTICLE

R. Daneshfaraz, M. Majedi Asl, R. Mirzaee, A. Ghaderi, The S-jump's Characteristics in the Rough Sudden Expanding Stilling Basin, AUT J. Civil Eng., 4(3) (2020) 349-356.

DOI: 10.22060/ajce.2019.16427.5586