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A Review Study on the Effect of Artificial Bed Roughness on the Performance of Prismatic Hydraulic Jump Stilling Basins

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Abstract. Hydraulic jumps offer an efficient method of dissipating excess kinetic energy beneath hydraulic structures such as chutes, spillways, and gates. Typically, the performance of a hydraulic jump stilling basin is measured in terms of the jump features it assigns: the basin must be both efficient in terms of energy dissipation and economical in terms of financial considerations. Corrugated and roughened beds are an alternative to the smooth beds commonly used in hydraulic jump stilling basins, and the effects of artificial roughness and corrugated beds on the performance of hydraulic jump stilling basins with respect to energy dissipation and jump length are thus reviewed in this study. Rough beds were thus found to have significantly higher shear stress than smooth beds, making them superior to smooth beds in terms of reducing basin length and enhancing energy dissipation.

Keywords: Corrugation, Energy dissipation, Hydraulic jump, Roughness, Stilling basin, Smooth bed.

INTRODUCTION

Water flowing through a gate or pipe outlet or over a spillway has a very high level of kinetic energy due to all of its potential energy being converted into kinetic energy. If such high-velocity water is released directly into the downstream channel, significant scour may occur in the downstream area, which, if not effectively controlled, may also go backward towards the hydraulic structure, endangering it. Energy dissipaters, also known as stilling basins, are structures designed to decrease incoming flow velocity and protect downstream regions from erosion; energy dissipation structures in use include hydraulic jump stilling basins, solid roller bucket energy dissipators, slotted bucket type energy dissipators, and interacting jet type energy dissipators. However, hydraulic jump type stilling basins, although more expensive, are generally the best option for energy dissipation. The performance of any stilling basin is typically determined by the properties of the entering flow, the available depth of tailwater, and the characteristics of the jump assigned. The length of the hydraulic jump is thus often used as a design parameter or as an indicator of the stilling basin length. From an engineering perspective, the stilling basin length must be both efficient in terms of energy dissipation and economical in terms of financial considerations, and in order to achieve the most effective design, the length of stilling basin should be kept as short as practicable [1][2]. The designer should be focused on the jump height within stilling basin to ensure a safe height for the side walls with sufficient free board; the lower the subsequent depth, the shorter the side wall height required. Based on bed characteristics, hydraulic jumps are classified into two types: classical and forced hydraulic jumps. The term "classical jump" refers to a jump formation in wide rectangular channel with a horizontal smooth bed, and researchers have focused a lot of attention on the classical jump in recent decades [3-12].

For classical jumps, the depth ratio can be calculated using the well-known Belanger equation first developed in 1828 [13]:

$$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1+8{Fr_1}^2}-1\right) \quad (1)$$

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$$Fr_1 = v_1/\sqrt{gy_1} \tag{2}$$

where $y_2,\ y_1, Fr_1, v_1, and\ g$ are the subcritical sequent depth, supercritical depth upstream of the jump, upstream Froude number, supercritical stream velocity, and gravitic acceleration, respectively.

Forced hydraulic jump occurs over an artificially or naturally rough bed, however, and this has also attracted the interest of many researchers [14], roughing the bed of the basin with certain materials can provide three advantages for a stilling basin, which are higher dissipation of kinetic energy, shorter jump length, and a lower subsequent depth ratio. The goals of all roughness elements are to stabilise the hydraulic jump position and create turbulence: by keeping the length of basin as short as possible, the most cost-effective design can also be obtained [15]. Shape, arrangement, dimensions, and intensity are the roughness parameters that have received the most attention, with relative roughness and approaching flow conditions having the most significant influence on the behaviour of hydraulic jumps [16-19]. In the literature, stilling basins with roughened beds studies were first comprehensively investigated by Rajaratnam in 1968 [10]. He developed the relative roughness parameter (k_e/y_1), where k_e is the equivalent roughness element, and confirmed that the length of the jump and the length of the roller on rough bed decrease significantly in such cases as compared to the same parameters in jumps on a smooth bed, as shown in Fig.1.

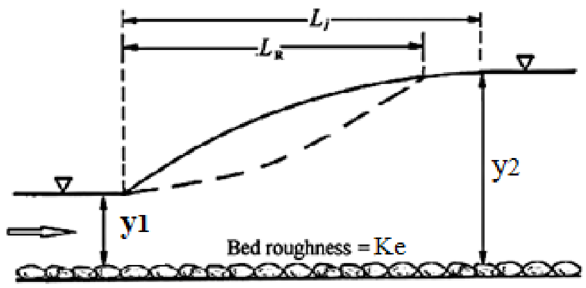

FIGURE 1. Hydraulic jump sketch for rough bed condition

Later, [20] proved that the supercritical flow downstream of the spillways or gates on rough beds require shorter basin lengths than those on smooth beds, and that the boundary layers form more rapidly on rough bed [20]. These findings were later confirmed by [21] and [16] for various artificially roughened beds in a rectangular horizontal channel with smooth side walls [21][16]. [16] designed a physical model to study the effect of bottom friction on conjugate depth ratio that showed that this ratio is affected not only by the Froude number, but also by the aspect ratio and upstream Reynolds number [16]. In addition, [22] developed a mathematical model to determine the sequent depth ratio of a hydraulic jump on horizontal roughened bed with and without steps [22].

Designing a stilling basin with a corrugated bed has the same effect as installing additional energy dissipation structures such as blocks and tail piers on the basin's bottom [23]. Corrugation acts as a uniformly artificially roughed base plate that can significantly increase hydraulic jump turbulence and thus reduces the energy carried by flowing water. Thus, the energy dissipation structure and riverbed both become less scoured or eroded, and the rate of energy dissipation increases [23]. Recently, various corrugation bed forms have been investigated, including triangular shapes [14][24-33].

Roughness intensity (I) is the ratio of the projected area of elements to the overall roughness area in the basin [34][35]:

$$I = 100 * \frac{a\ n}{B\ L_r} \tag{3}$$

where
B: basin width
L_r: roughened length,
a: plane area of single element, and
n: roughness elements number.

Many researchers have thus investigated the effects of roughness intensity on stilling basin performance [2][34-39]. The ideal intensity for cubic bed roughness, according to [36][39], is 10%, which applies from both an economic and hydraulic standpoint. [36][39]. This intensity was thus used by [40] to create optimal stilling basin design equations using cube roughness elements under various flow conditions.

Roughness elements are exposed to cavitation due to the high velocity of the incoming jet, ad in order to avoid cavitation, any corrugations and roughness element crests must be placed in the basin's bed such that their crests are at the same level as the upstream bed [14][41-44]. According to [31], rounding the crests of roughness elements can reduce or eliminate the length of the separation zone, thereby reducing the risk of cavitation. As a result, sinusoidal corrugated beds with rounded crests are recommended over other corrugated bed shapes [31]. Despite the fact that many numerical and experimental studies on stilling basins with roughness bed have been published, however, only a few review studies have focused on the effect of corrugation and roughness element characteristics on basin length and energy dissipation. This makes it crucial to shed light on the most relevant studies related to this topic, and this paper thus provides a comprehensive review of the available literature on the effect of artificial bed roughness on the performance of horizontal prismatic hydraulic jump stilling basins in terms of reducing basin length and increasing energy dissipation.

EFFECT OF ARTIFICIAL ROUGHNESS BEDS ON STILLING BASIN PERFORMANCE

Stilling Basin Length

Hydraulic jump length is usually utilized as a design criterion for downstream paved length, also known as the stilling basin length. Pavement can protect the basin from scouring caused by the high kinetic energy through-flow, yet from an engineering aspect, stilling basin length must also be efficient in terms of energy dissipation and inexpensive in term of fiscal effects. This makes it important to design the basin to be as short as possible, and basins are thus rarely designed to contain the mature length, or the entire length where flow profiles are fully developed, as these would be prohibitively long [13].

The relative jump length (L_j/y_2) of a classical hydraulic jump depends on the upstream Froude number for (Fr1 < 5), achieving a constant value of 6.1 for Fr1 > 5. Equation (4) is used to compute the possible reduction in length of hydraulic jump over a rough bed [45]:

$$L_x = \frac{L_o - L_j}{L_j} * 100 \tag{4}$$

where Lx is the jump length reduction (%), and L_o and L_j are the lengths of hydraulic jumps over smooth and roughness beds, respectively.

With regard to roughness components, the effect of cube-shaped elements on jump length and, thus, the length of stilling basins has been investigated by many researchers [36][34][46][39][47][10]. [39] showed that utilising cube roughness at 10% intensity shortened the length of the hydraulic jump substantially [39] in a manner consistent with the USBR (basin II) results for large Fr_1 values, as well as showing higher reductions for Fr_1 values less than 6. That work also noted that reducing the length/height ratio of the block element improved the stilling basin's efficiency by reducing the relative length of the jump, which reached a minimum value when this ratio equalled 28. [35] proved that T-shape roughness elements reduce the length of the jump while requiring fewer materials than cubic roughness. When compared to a smooth bed, a T-shape bed reduces the relative length of jump by 28 to 42% for Fr_1 values between 3 and 9 at an intensity of 8% [35]. [38], on the other hand, claimed that the U-shape roughness elements were superior to cubic ones and could reduce relative jump length by 28 to 47 % for Froude numbers ranging from 3 to 11 at an intensity of 12.5%. Further sensitivity analysis revealed that, for the U-shaped bed, when the values of intensity and roughness length increased above their optimal values, the length of the jump remained more sensitive to the intensity than the roughness length, whereas when the values of intensity and roughness length decreased below their optimal values, the length of the jump was more sensitive to the roughness length [38].

Using wedge-shaped roughness on the bed was found in [48] to reduce hydraulic jump length by up to 53% as compared to a smooth bed, thus decreasing the relative length of the jump as the initial Froude number increasesClick or tap here to enter text.. This conclusion contradicted [39] findings about cubic blocks, which suggested that the value of relative length increases as the value of the initial Froude number increases, however. The cause of this disagreement was explained by [48] as being due to the fact that the cubic blocks protruded into the flow, whereas the crests of wedge-shaped roughnesses were at the same level as the upstream bed carrying the supercritical flow [48]. [49] concluded that using lozenge-shaped rough bed elements reduces basin length to as low as 40% of standard [49], while according to [44], semi-circular elements downstream of an ogee spillway can reduce the length of the stilling basin by 56% as compared to a regular basin, with a reduction of more than 15% even as compared to the lozenge type used by [49] under the same Froude number range conditions [44]. [37] investigated the efficiency of six-legged concrete (SLC) pieces downstream of a spillway chute with Froude numbers ranging from 5.3 to 8.1 and varying densities: in comparison to the smooth bed, SLC elements reduced jump length by about 29%, 23%, and 17% for densities of 36%, 63%, and 100%, respectively [37].

A corrugated bed creates a uniformly roughed floor that can considerably increase hydraulic jump turbulence and hence decrease basin length, and such corrugation can take various shapes, including sinusoidal, trapezoidal, triangular, and rectangular. [14] discovered that the jump length on a sinusoidal corrugated bed with a wavelength (s) and a wave height (t) was approximately half that of a smooth bed, and that the integrated shear stress of a corrugated bed was approximately ten times more than that of a smooth bed [14]. Furthermore, [33] found that the relative jump length over a sinusoidal corrugated bed was about 35% less than that of an equivalent smooth bed [50] analysed experimental data on a sinusoidal corrugated bed, as well as data from [14], noting that the length of the jump was almost three times the subcritical depth (y_2) of the classical jump, which is equivalent to a half-length of the classical jump. [50]further stated that the relative sizes of the corrugated bed within the data set investigated (1.7 <Fr_1< 7, 0.55< t/y_1< 0.75, 1.36 < s/y_1 < 3.75) had no significant effect on hydraulic jump parameters, as the corrugations, with their crests at the upstream bed level, behaved more like cavities, and thus the values of s/y_1 and t/y_1 were insignificant [50]. [24] performed a study on sinusoidal corrugated beds that showed that the Froude number had a significant influence on the jump length [24], however, while [51] stated that the lengths of jump on various corrugated beds (sinusoidal, triangular, trapezoidal) were less than half those seen on smooth beds, with the integrated bed shear stress on the corrugated beds being more than fifteen times that on smooth beds [51].

For trapezoidal shaped corrugated beds, [42]showed that the relative jump length (L_j/y_2) was independent of the Froude number and was reduced by half as compared to that seen in smooth beds [42]. The length of the jump was also shown to be highly dependent on the corrugations' spacing (s) rather than their amplitude (t). Triangular, trapezoidal, and semi-circular corrugated beds decreased jump length by around 14%, 11% and 10%, respectively, though corrugated beds had an insignificant effect on the jump length when $Fr_1 < 3$ [25]. Based on [32], triangular corrugated beds cause the hydraulic jump length to be reduced by 54.7% as compared to smooth beds, though effect of the corrugation shape is nearly insignificant [32] as shown in Fig. 2.

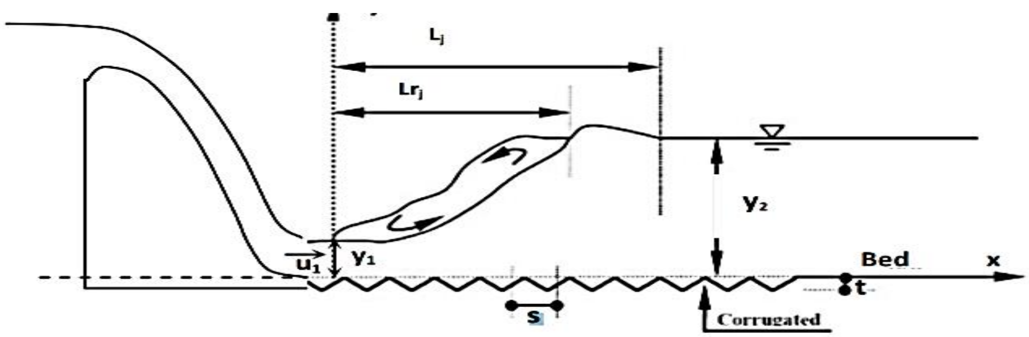

FIGURE 2. Hydraulic jump over triangular corrugation bed

Another study by [26] confirmed that a triangular corrugated bed reduced the jump length by about 21% when the corrugated space was three times roughness height and Fr_1 =1.68 to 9.29 [26]; while [27] found that triangular corrugated beds reduced hydraulic jump length by up to 10%, the shape of the corrugation had relatively less impact on hydraulic jump characteristics for low Froude numbers [27]. [52]indicated that t triangular corrugated beds with 45° and 60° slopes reduced jump lengths by up to 24%, and 28%, respectively, and the shapes of the corrugation bed had significantly less effect on hydraulic jump properties for low Froude numbers, with a greater impact seen for higher numbers (Gandhi, 2018b). According to [53], triangular corrugation has a significantly higher influence on the length of the jump as compared to semi-oval and square shapes, minimising the relative length of jump by about 25.5% when t/s =0.5 [53]. For rectangular shaped corrugated beds, according to [54], [27], and [53], however, jump lengths were reduced by up to 25%, 7% and 22% for Froude numbers in the ranges 8.6 to 13.3, 2.75 to 4.25, and 1 to 4, respectively.

Relative Energy Dissipation

The dissipation of kinetic energy is the most important parameter used as an indicator for the performance of hydraulic jump stilling basins. The main sources of energy loss during a hydraulic jump are turbulent stream and secondary waves [54], and the interaction forces between supercritical flow and a rough bed increase bed shear stress and eddy viscosity significantly, especially at large Froude numbers, which decreases the hydraulic jump length and subsequent depth [23][26][38][55].

Generally, energy loss depends on the basin's geometric and hydraulic parameters [40]. Energy loss (E_L) in the jump equals the difference between the specific energy before and after the jump, $E_1$and E_2. Factor G can thus be used to define the gain in the energy dissipation, as follows:

$$G(\%) = \frac{E_L - E^*_L}{E^*_L} * 100 \tag{5}$$

where $E_L$and E^*_L are the energy losses in forced and classical hydraulic jumps, respectively, for the same upstream conditions y_1 andFr_1.

In terms of roughness elements, [35]found that T-shaped elements increase relative energy loss by 14% at optimum roughness intensity; however, increasing the roughness length had no effect on energy loss, with the most cost-effective relative roughness length (L_r/y_1) being equal to 16 [35]. According to [35], bed shear stresses are higher in U-shaped roughened beds than in cubic and T shapes, however, due to the interaction of supercritical flow with eddies trapped in the U-shaped cavities, which increases the related excessive localised eddies and turbulence caused by the moving fluid masses, resulting in high energy losses [38]. [56] observed that increasing the roughness length for cubic elements arranged in a staggered manner does not make a significant difference to energy loss, however, while increasing the roughness height does make a significant difference to hydraulic jump characteristics [56]. [1]found that the staggered arrangement of rectangular prismatic bars at 3.5 < Fr_1 < 11 increases the amount of dissipated energy by 6%, whereas a strip pattern with 2.5 < Fr_1 < 16.6 increases it by 4.9% [1]. According to [57], vertical semi-circular and vertical trapezoidal shaped baffle piers arranged in a single line downstream of the spillway dissipate more energy than other models studied, while solid sills dissipate less [57]. [54] stated that rectangular strip roughness produced approximately 2 to 3% more energy dissipation than a conventional jump [54], while [58] showed that energy loss increases by 34.6 % and 36.6 %, respectively, for strip and staggered semi-circular beds with intensities of 25%, as compared to a standard hydraulic jump. Shear stress was also found to be approximately eight times greater in a staggered bed than in a smooth bed [58]. [44] observed that energy dissipation for prismatic semi-circular bed elements downstream of an ogee spillway was about 8% higher than for smooth beds when $Fr_1 = 4$ to 11 [44]. According to [2], stilling basins with cubic shaped roughness elements that did not protrude into the flow resulted in higher energy dissipation, ranging from 10.8% to 22.3% when $Fr_1 = 2.7$ *to* 9 and I=12%: they also demonstrated that changes in intensity had no effect on the quantity of energy dissipated along the jump, whereas changes in width to height and length to height ratios had a substantial effect on the rate of energy dissipation [2].

With respect to corrugation roughness, [33] plotted the relative energy loss versus the Fr_1 for sinusoidal corrugated beds using primary data where $t/s = 0.2$ *and* 0.26), along with data from [14]who used $t/s = 0.191$ *and* 0.324, as illustrated in Fig. 3 [33]. As shown, corrugated beds were seen to dissipate more energy than smooth beds for the same Froude number. [33] observed that as the Froude number increases, the gain in energy loss for jumps on corrugated beds reduces, tending towards a constant value of 6% for Froude numbers higher than 8. As per [24], the energy loss at a sinusoidal corrugated bed was 5 to 19% higher than on the equivalent smooth bed, being around 10% when $Fr_1 > 7$ [24].

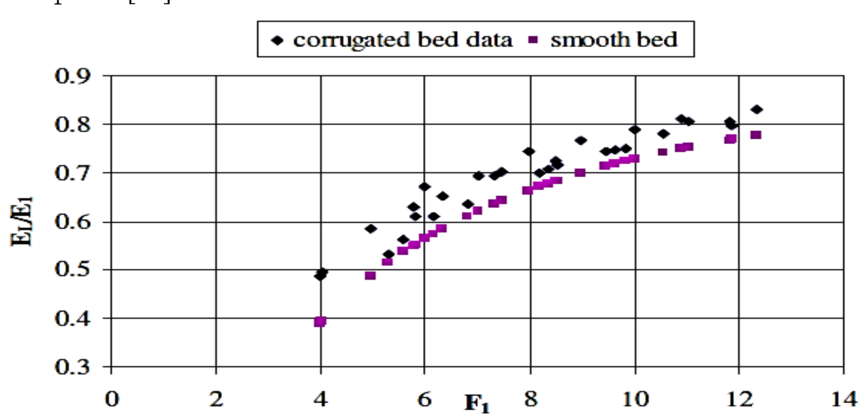

FIGURE 3. Relative energy loss between smooth and sinusoidal corrugated beds

[59]confirmed that the sinusoidal corrugated bed was more efficient for energy dissipation than smooth, trapezoidal, or triangle beds, with bed shear stress al so greater in the sinusoidal corrugated bed, as shown in Fig. 4. Energy dissipation on the sinusoidal bed is approximately 22% greater than on the smooth bed for Fr1 <5 and though less than 2.5% greater for Fr1 >5 [59].

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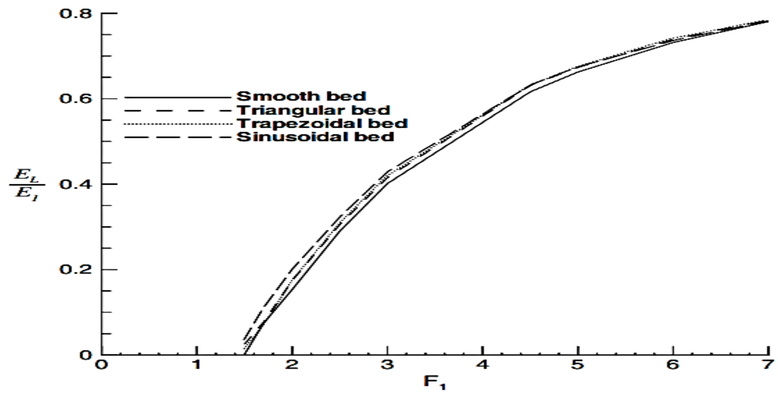

FIGURE 4. Relation between energy dissipation and initial Froude Number

For a triangular corrugated bed, [32]observed that the energy loss was 11% higher than on a smooth bed with same Froude number [32]. Further, when compared to a conventional jump, [26] found that the triangular corrugated bed increased jump efficiency by 50.3% at optimal spacing roughness, which was found at three times the height [26]. According to [27]; triangular, rectangular, and circular corrugated beds lowered tail water depth by about 9%, 8%, and 11.5%, respectively, with jump length lowered by up to 10%, 7%, and 11%, respectively, as compared to the measures for an equivalent smooth bed surface. According to [52], triangular (45° slope and 60° slope) corrugated beds increased energy dissipation by up to 27% as compared to smooth beds, while for higher Froude numbers, energy dissipation was greater in a logarithmic fashion for the tested beds; these results were compared with those [59], which showed the same variation, with only such divergence as may be due to different experimental conditions [52]. According to [60], a triangular corrugated bed with t/s = 0.50 dissipated the most energy as compared to semi-oval and square designs [53]. Table 1 summarises some of the details of the studies discussed in this paper.

TABLE 1. Test Model Specifications and Test Conditions

Authors	Roughness shape	Limitations of study			Empirical Equation
		Fr_1	Geometry	I %	
Mohamad Ali, 1991 [39]	cubic elements	4.47-9.53	(L_R/h)= (18-125)	10	$\frac{L_j}{Y_1} = 38.7\ ln\ Fr_1 - 43.88$
Alhamid, 1994 [34]	cubic elements	3.4 - 7.0	(1.2*1.2*3) cm	0-20	$\frac{L_j}{Y_1} = 7.71\ Fr_1 - 1.42I + 0.05I^2 + 0.0549IFr_1$
Ead and Rajaratnam, 2002 [14]	Sinusoidal corrugated	4-10	t/s= (0.19 & 0.32)	-	$\frac{L_j}{Y_1} = 1.74\ Fr_1 + 3.62$
Tokyay, 2005 [33]	Sinusoidal corrugated	5-12	(t/s) =0.2 & 0.26	-	$\frac{Y_2}{Y_1} = 1.1223\ Fr_1 + 0.0365$
Izadjoo and Shafai 2007 [42]	Trapezoidal corrugated	4-12	t/s= (0.21-0.38)	10	$\frac{Y_2}{Y_1} = 1.047\ Fr_1 + 0.59$
Bejestan and Neisi, 2009 [49]	Lozenge-elements	4.5-12	(1.6*1.6*1.6) cm	-	$\frac{L_j}{Y_2} = 6.281e^{-0.035\ Fr_1}$
Abbaspour et al., 2009 [24]	Sinusoidal corrugated	3.8- 8.6	0.286 ≤t/s ≤ 0.625	-	$\frac{Y_2}{Y_1} = 1{:}\,1146\ Fr_1$
AboulAtta et al., 2011 [35]	T-shaped elements	3.0 – 9.0	Lr = (9.2 - 120) cm	4.3-21.6	$\frac{\Delta E}{E_1} = a + b \ln Fr_1$ a and b constants depending on roughness length
Ezizah et al., 2012 [38]	U-shaped elements	3.0 -11.0	Lr = (15 -100) cm	4.5-18	$\frac{L_j}{Y_1} = c + d \ln Fr_1$ c and d constants depending on roughness length
Samadi-Boroujeni et al., 2013 [32]	Triangular corrugated	6.1- 13.1	0.22 ≤ t/s ≤ 0.29	-	$\frac{\Delta E}{E_1} = 0.3744\ {Fr_1}^{0.323}$
Ahmed et al., 2014 [26]	Triangular strip corrugated bed	1.68- 9.29	t/s = (0.2-0.5)	-	$\frac{L_j}{Y_1} = 5.6078{Fr_1}^{0.8019}$ $\frac{E_2}{E_1} = 11.88{Fr_1}^{0.9188}$
Deshpande et al., 2016 [58]	Semi-circular staggered& strip corrugated bed	2.5 - 6.2.	t/s= (0.1-0.25)	20-50	$\frac{\Delta E}{E_1} = 0.09\ Fr_1 + 0.15$ $\frac{L_j}{Y_1} = 4.4\ Fr_1 - 2.5$
Hayder, 2017 [44]	Semicircular -shaped roughness bed	4-11	height = 2.7 cm space= 5 cm	-	$\frac{L_j}{Y_2} = 3.7377 \ln Fr_1 - 3.2462$
Maatooq and Taleb, 2018 [2]	Cube-shaped element	2.7 – 9.0	Width/height= (0.75& 1.5) Length/height = (2 &4)	8- 16	$\frac{\Delta E}{E_1} = -0.0112Fr_1^2 + 0.223Fr_1 - 0.321$
Ghaderi et al., 2020 [53]	triangular, semi-oval, and square corrugated bed	1.7–9.3	t/s=0.5 &0.2	-	$\frac{\Delta E}{E_1} = -0.0104Fr_1^2 + 0.191Fr_1 - 0.205$

CONCLUSION

Hydraulic jump stilling basins are preferred by most designers for energy dissipation downstream of spillways, gates, and outlets, as a well-designed stilling basin can provide high energy dissipation over a short length. A review of previous research shows that a stilling basin with a rough bottom can effectively improve energy dissipation, shortening the length of the basin, and thus minimising stilling basin costs. The following results were obtained from the review of studies examining the best design of artificially rough bed stilling basins:

- To avoid cavitation, the upper surface of roughness (crest) should be placed at the same level as the upstream bed, while to reduce cavitation, sinusoidal corrugated beds are favoured over other corrugated designs.
- Wave length has a greater influence on jump length than corrugation height.
- Bed shear stress is significantly higher in rough beds than in smooth beds depending on the type of roughness. Furthermore, shear stress was affected by the initial Froude number.
- The shape of the corrugated bed has little effect on hydraulic jump characteristics at low Froude numbers, though it is more significant at higher ranges.
- Increasing roughness length has little effect on energy loss.
- Placing roughness elements in a staggered arrangement helps to dissipate more energy than using a strip arrangement.
- As bottom shear stress is greater in sinusoidal corrugated beds, these are more efficient for energy dissipation than other corrugation shapes.
- Further studies are required for roughness beds with high Froude number before field applications commence.

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