Arab Gulf J. Scient. Res., **17** (1), pp. 35-47 (1999)

Effect of Roughness Height on the Performance of Stilling Basins

Abdel-Azim M. Negm,[1] Ehab M. Wafaie[2] and Abdul-Aziz A. Al-Othman[3]

[1]*Water and Water Structures Engineering Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt*
[2]*Civil Engineering Department, Al-Mataria Faculty of Engineering and Technology, Hellwan University, Hellwan, Egypt*
[3]*Civil Engineering Department, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia*

ABSTRACT. This study presents the results of experiments on the effect of roughness height on the performance of hydraulic jump type stilling basins. The length of jump is taken as the main criterion for the length of the stilling basins. The experimental work is conducted on a large laboratory flume to minimize side wall effects. Non-dimensional empirical formulae are developed to compute the length of the hydraulic jump in terms of the roughness height ratio and the approaching flow Froude number. Design curves and equations are also provided for field applications.

It is generally known that hydraulic jump primarily serves to dissipate the excess energy of flowing water downstream of hydraulic structures, such as spillways and sluice gates. A hydraulic jump may occur when a supercritical flow under a sluice gate transferred into a subcritical stream of sufficient depth downstream. While doing so, it generates considerable disturbances in the form of large scale eddies and a reverse flow roller resulting in energy dissipation. Fig. (1) is a schematic sketch of a typical hydraulic jump downstream of a sluice gate with a roughened bed. Out of many devices adopted for energy dissipation below hydraulic structures, stilling basin having hydraulic jump is the most common one. In the design of stilling basin, the length of jump, L_j - a distance from the front of jump (toe) to the end of the roller (the largest extent of the surface separation zone) must be known. Dimensional considerations with experimental evidence have shown that the jump length is a function of flow and roughness parameters. The basic similarity parameter is the approaching flow Froude number. While the roughness parameters include type and shape of roughness, way of arrangement, height of elements, h_b, and its density, I. In practice, the stilling basin is seldom designed to conform to the length of free hydraulic jump because such a basin would be too expensive. Baffles and sills are commonly used as devices to stabilize the hydraulic jump in the stilling basins USBR (1958) and Visher and Hager (1995). The use of roughened stilling basins in horizontal channels is also reported by Hager (1992). Mohamed Ali (1991) concluded that the length of hydraulic jump is clearly reduced by using cube roughness elements for Froude number up to 10. The use of roughness is to increase the turbulent motion of the high velocity of flow and the shear action of the roller. Consequently, the energy dissipation is increased and the jump length is reduced. Many studies dealing with the effect of roughness elements on the hydraulic jump include the works of USBR (1958), Rajaratnam (1968), Leutheusser and Schiller (1975), Gill (1980), Ranga Raju *et al.* (1980), Hughes and Flack (1984), Abdelsalam *et al.* (1986), Hammad *et al.* (1988), Ohtsu *et al.* (1991), Negm (1993), Negm *et al.* (1993a, 1994), Alhamid (1994) and Alhamid and Negm (1996). The studies of Abdelsalam *et al.* (1986), Negm *et al.* (1993b) and Alhamed (1994) proved that the most efficient roughness is the rectangular one when arranged in a staggered way with density equal to or about 10%. The review of literature showed that little information regarding the effect of height of roughness elements on the length of jump has been reported, see *e.g.* Hammad *et al.* (1988). Thus the present study was planned to investigate experimentally the effect of cube roughness height in staggered arrangement with fixed density of 10% under different flow conditions on the performance of stilling basins. The length of jump is taken as the main criterion during the discussion of the results.

Dimensional Considerations

Fig. (1) shows a definition sketch for the free hydraulic jump formed on rough bed downstream of sluice gate. Based on the dimensional analysis, the following non-dimensional functional equations can be written for the length of jump on the roughened bed:

$$L_j / y_1 = f_1 \left(F_1, I, \frac{h_b}{y_1}, \emptyset\right) \qquad \text{.................................... (1)}$$

where L_j is length of jump for rough bed, $F_1 = Q/(by\sqrt{2g})$ is the Froude number at or near vena contracta, y_1 is the initial depth of jump at vena contracta and y_2 is the downstream depth after the jump, h_b is the height of roughness element, I is the roughness density, ($I = aN/bL_R$), a is the plan projected area of the roughness element, N is the number of the roughness elements, b is the width of the flume L_R is the length of the roughness and φ is the shape factor. Defining C_L as the ratio between the length of jump on the rough bed to the length of jump on the smooth bed.

$$\frac{L_j}{y_1} = C_L \left(\frac{L_{jo}}{y_1}\right) \qquad (2)$$

C_L is the jump length conversion factor, L_{jo} is length of jump for smooth bed. Knowing that the length of jump on smooth bed is a function of F_1, C_L can be expressed as follows:

$$C_L = f_2 \left(F_1, I, \frac{h_b}{y_1}, \varnothing\right) \qquad (3)$$

In the present study, the staggered rectangular roughness is adopted with constant density of 10% based on previous studies of Abdel-Salam *et al.* (1986) and Negm *et al.* (1993c). Therefore the shape effect and the effect of the density on the length of jump can be ignored. Also, it is known that the sequent depth ratio is a function of h_b/y_1 and F_1. Thus for constant I and φ Eq. (3) becomes:

$$C_L = f_3 \left(F_1, \frac{h_b}{y_1}\right) \qquad (4)$$

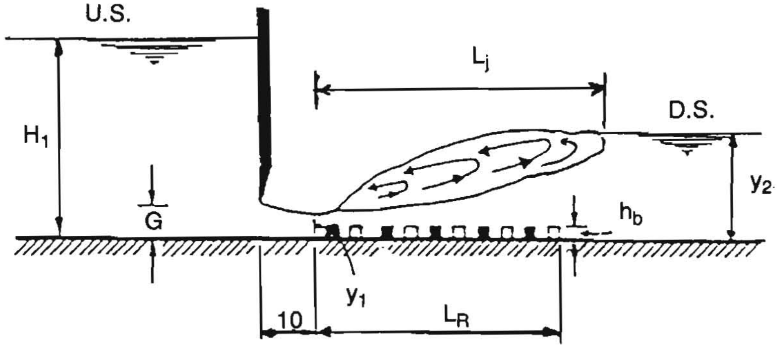

Fig. 1. Definition sketch for free jump formed on a rough bed.

Experimental Set-Up

The experiments were conducted in a 15 m long, 0.53 m wide and 0.7m deep glass walled recirculating flume. The water depths were measured by means of point gauges mounted on instrument carriages. The discharge was measured by a pre-calibrated orifice meter. The roughness elements were fixed to the bed starting about 10 cm downstream from the sluice gate to allow the jump to begin at or near the vena contracta. The roughness covered a length of 68.2 cm for density of 10%.

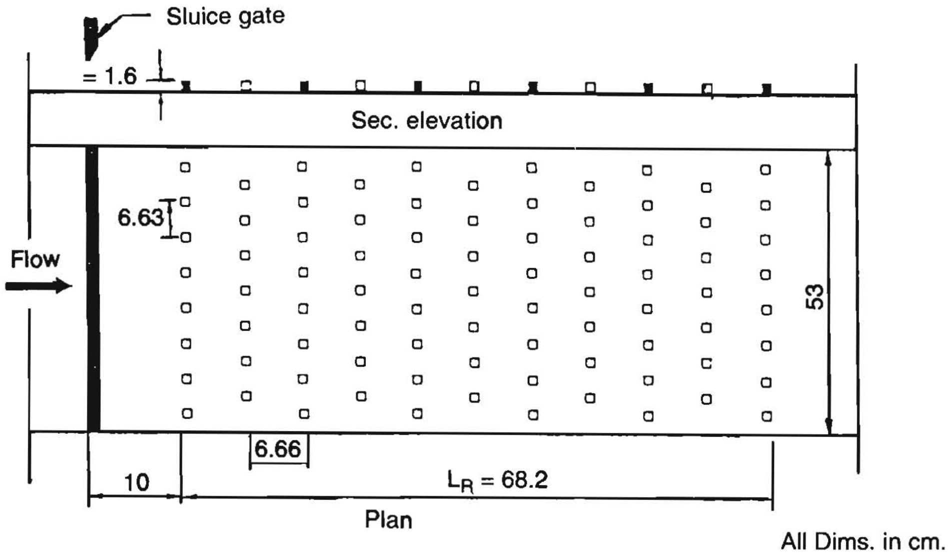

Fig. 2. Typical distribution of roughness elements for the tested models.

The elements were fixed to the bed by means of a rapid curing activator. Figure (2) presents a typical arrangement of the roughened bed to show the distribution of the roughness element over the channel bed. Five models were tested in this study. One is smooth and the other four are rough with fixed density of 10% using 1.6 cm square staggered elements in plan on 68.2 cm long roughened bed with heights of 0.8, 1.2, 1.6 and 2 cm. The discharges ranged between 21 l/s and 54 l/s and the approaching flow Froude number ranged between 4 and 9.5. Different gate openings were considered in the range from 2.5 to 5.5 cm. The test procedure consisted of the following steps:

i) The flume was adjusted to horizontal position.

ii) A desired gate opening and a specified discharge were set.

iii) The position of the jump was set by adjusting tail gate and waiting until stable conditions were attained at the desired location (vena contracta near the sluice gate keeping the tail gate at the same position for that specified discharge for all the tests.

iv) The flow rate, the water depths before the jump, y_1, and after the jump, y_2, when the water surface reaches nearly equal to the tail water depth were then measured.

v) The length of jump, L_j, was measured in each case from the toe of the jump (at the vena contracta) to the maximum surface after the jump.

vi) The procedure was the same for smooth bed and for all roughened beds under considerations.

The limitations of this study includes:

i) Length of jump is measured following the definition of USBR (1958).

ii) Downstream gate submergence is avoided ensuring the jump location which begins at or near the vena contracta.

iii) The data of the length of jumps, L_j is presented with a precision of ± 0.05 m owing to violent formation of eddies during measurements.

iv) The Froude number ranges between 4 and 9.5.

Analysis and Discussion of Results

Effect of roughness height on y_2/y_1 and E_1/E_1

Figure (3a, b) show the variations of y_2/y_1 and E_L/E_1 with F_1 for different h_b/y_1 ranging from 0 to about 0.8 (E denotes for the energy, E_L is the energy loss = E_1-E_2, with 1 and 2 denotes for sections at beginning and at the end of jump). It is noted that the roughness height has a very minor effect on these properties of the jump. This result corporates with the results obtained by USBR (1958) and Hammad *et al.* (1988). Thus, the influence of y_2/y_1 and E_L/E_1 are not considered for further analysis.

Effect of roughness height on L_j/y_1

Figure (4) shows the general variation of the length of jump ratio, L_j/y_1, with the initial Froude number, F_1, using different roughness height ratios, h_b/y_1, ranging from 0 to about 0.8. It can be seen that the roughness height ratio reduces the non-dimensional length of jump significantly which is due to large drag effect resulting from the increase in roughness height. The rate of reduction depends on both the initial Froude number and the height of roughness ratio. Fig. (5) demonstrates the effect of roughness height ratio, L_j/y_1, at constant values of F_1 (F_1 = 3.5, 4.5, 5.5, 6.5 and 7.5). From this figure, it can be noted that, L_j/y_1, is reduced with increasing h_b/y_1 at a remarkable rate. Using statistical methods, it was possible to obtain the following formula for both the length of jump ratio.

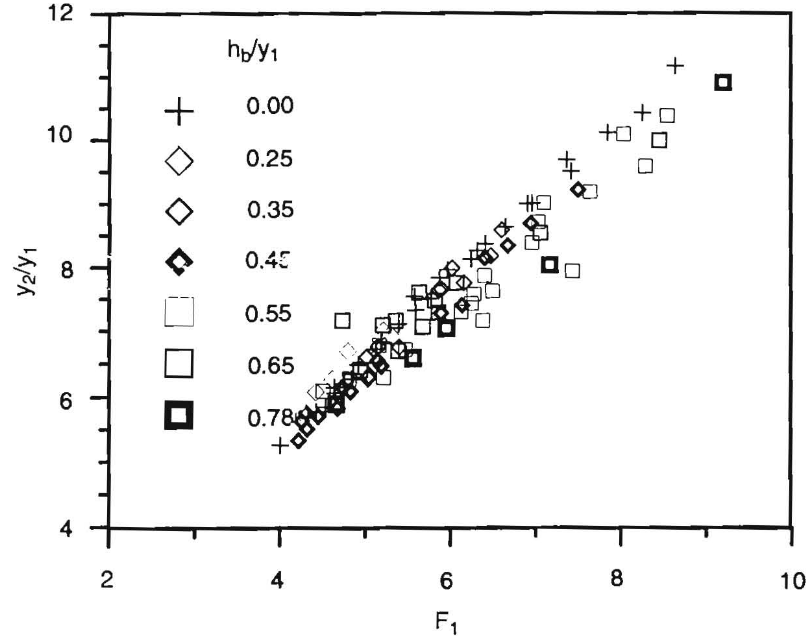

Fig. 3a. Variation of y_2/y_1 with F_1 for different h_b/y_1.

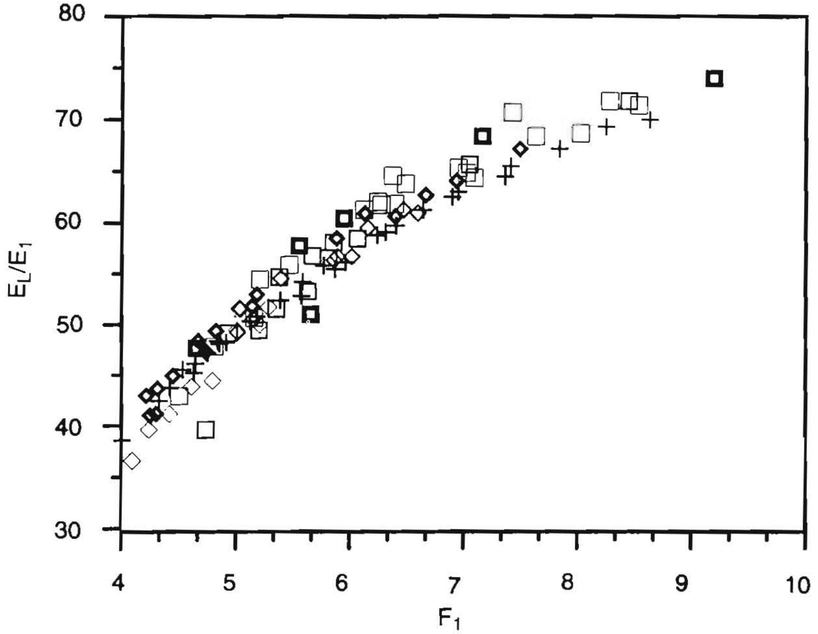

Fig. 3b. Variation of E_L/E_1 with F_1 for different h_b/y_1(notations as in 3a).

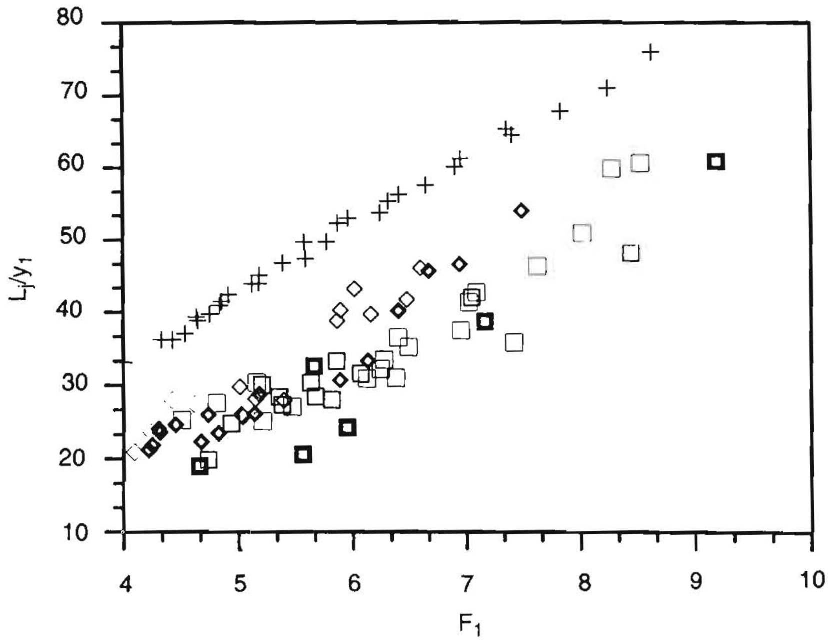

Fig. 4. Variation of L_j/y_1 with F_1 for different h_b/y_1.

$$\frac{L_j}{y_1} = C_o + C_1\left(\frac{h_b}{y_1}\right) + C_2\left(\frac{h_b}{y_1}\right)^2 \qquad \text{.................................... (5)}$$

where C_o, C_1 and C_2 are constants and their values depend on the approaching Froude numbers. The values of these constants as obtained by regression analysis are presented in Table (1).

Table 1. Values of the regression coefficients of equation (5).

F_1	C_o	C_1	C_2	Remarks
3.5	27.647	-61.049	54.523	Eq. (5)
4.5	37.655	-52.785	37.885	
5.5	47.673	-44.525	21.253	
6.5	57.686	-36.261	4.6215	
7.5	67.699	-28.006	-12.012	

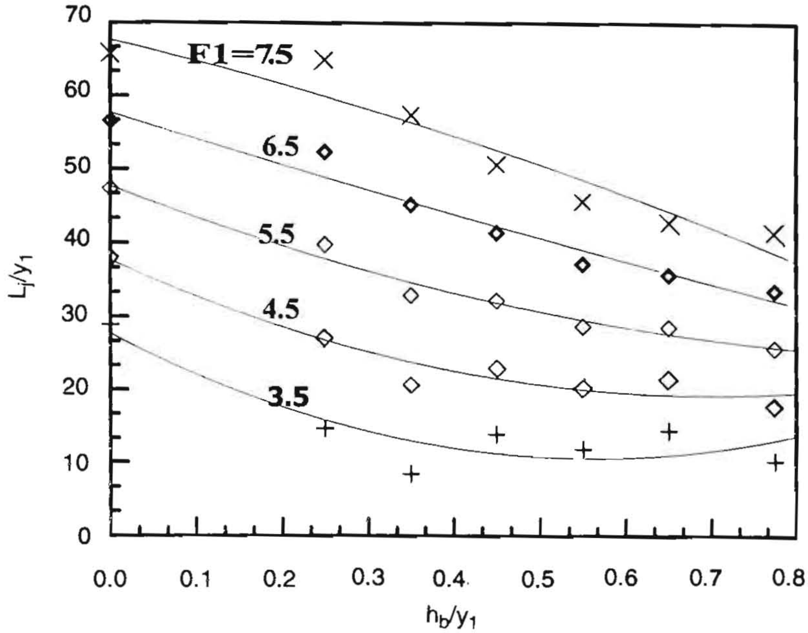

Fig. 5. Variation of L_j/y_1 with h_b/y_1 for different values of F_1.

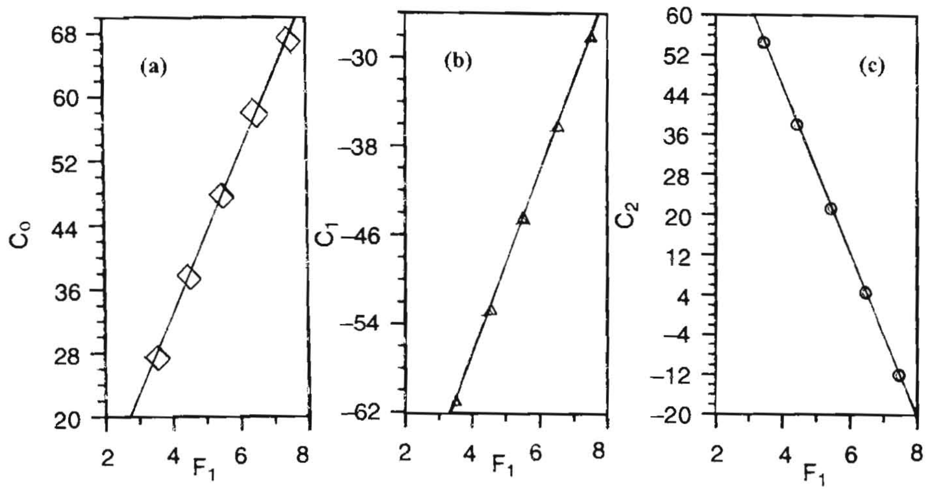

Fig. 6. Relationship between (a) C_o of Eq. (6); (b) C_1 of Eq. (7) and (c) C_2 of Eq. (8) with F_1.

The variations of C_o, C_1 and C_2 with F_1 are shown in Figures (6a, b, c) to enable the use of equation (5) for any value of F_1 within the experimental range. The relationships between C_o, C_1 and C_2 with F_1 are straight lines with the following equations:

$$C_o = 10.0135\, F_1 - 7.40225 \quad \text{.................................... (6)}$$

$$C_1 = 8.261\, F_1 - 89.9607 \quad \text{.................................... (7)}$$

$$C_2 = -16.6333\, F_1 + 112.737 \quad \text{.................................... (8)}$$

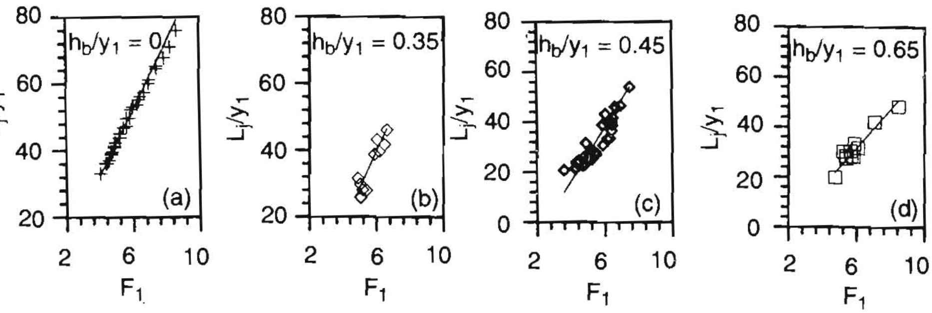

Fig. 7. Measured length of jump ratio versus the predicted using Eq. (5).

The prediction of equations (5) is compared with the experimental data Fig. (7). Fig. (7) shows that the results of equation (5) agrees well with the experimental data.

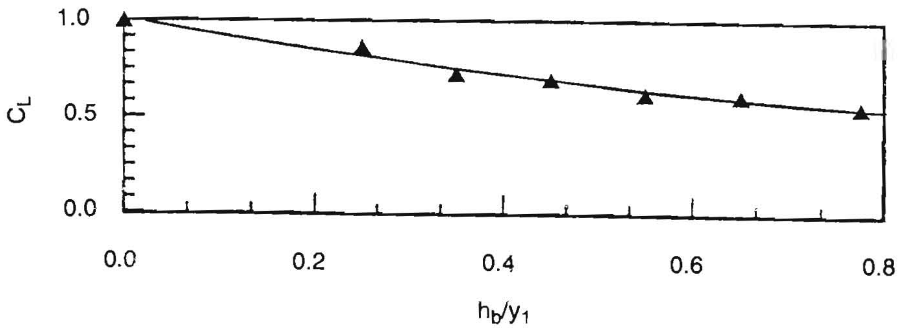

Fig. 8. Relationship between C_L and h_b/y_1 for jumps on rough beds.

Design Curves and Formula

For the design purposes, Fig. (8) shows the jump length conversion factor C_L

versus h_b/y_1 at density of 10% with staggered rectangular roughness for average flow conditions. In general the effect of roughness height ratio on both L_j/y_1 is significant compared to the smooth bed case. The following design formula for C_L is obtained using statistical methods:

$$C_L = 1.01103 - 0.85578\left(\frac{h_b}{y_1}\right) + 0.3453\left(\frac{h_b}{y_1}\right)^2 \qquad \text{.............. (9)}$$

Conclusions

1. The analysis of results proved that the length of free hydraulic jump over roughened bed downstream of the sluice gate is function of the approaching flow Froude number, F_1, and roughness height ratio, h_b/y_1, for particular roughness shape at constant density of roughness.

2. The roughness height ratio, h_b/y_1, reduces signifiantly the jump length at a gradually rate compared to the smooth bed. The range of $h_b/y_1 = 0.5$ to 0.6 is recommended for design.

3. The jump length conversion factor, C_L, has been presented so that it is easy to calculate the jump length under the effect of roughness height for the optimal roughness density. The experimental range of this study is as follows:

$$I = 10\%,\ 0 < h_b < 0.85,\ 4 < F_1 < 9.5.$$

Notations

a	: plan projected area of one roughness element.
b	: width of the test flume.
C_o-C_2	: Regression constants.
C_L	: jump length conversion factor.
F_1	: Froude number of approching flow before jump.
h_b	: height of roughness element.
I	: roughness density.
L_{jo}	: length of jump for smooth bed case.
L_j	: length of jump for rough bed case.
L_R	: length of roughness.
N	: number of roughness elements.
Q	: discharge passing through the flume.
y_1	: initial depth of jump.
y_2	: sequent depth of jump.
ø	: shape factor.

References

Abdelsalam M, W., Elniazy, H.M., Abdelkawi, K. and **Abdellateef, M.** (1986) Roughened Bed Stilling Basin, *Scientific Bulletin,* Faculty of Engineering, Ain Shams University, Cairo, Egypt, **19**(1): 178-198.

Alhamid, A.A. (1994) Effective Roughness on Horizontal Rectangular Stilling Basins, in Free Surface Flow and Hydraulic Modelling, **Blain, W.R.** and **Katsifarakis, K.L. (eds).** Proceedings of the 5^{th} Int. Conf. on Hydraulic Engineering Software, Computational Mechanics Publications, Southampton, **2:** 39-46.

Alhamid, A.A. and **Negm, A.M.** (1996) Depth Ratio of Hydraulic Jump in Rectangular Stilling Basins, *J. Hydraulic Research,* **34**: 597-604.

Gill, M.A. (1980) Effect of Boundary Roughness on Hydraulic Jump, Water Power and Dam Construction, **32**(1): 22-24.

Hager, W.H. (1992) *Energy Dissipators and Hydraulic Jump,* Kluwer Academic Publishers, Dordrecht, The Netherlands.

Hammad, M.E., Abdelkawi, Kh., Talaat, A.M., Abdellateef, M. and **Wafaie, E. M.** (1988) Optimum Height of Bed Roughness in Stilling Basins, *Bulletin of The Faculty of Engineering,* Ain Shams University, Cairo, Egypt, **22**(1): 59-73.

Hughes, W.C. and **Flack, J.E.** (1984) Hydrualic Jump Properties Over a Rough Bed, *J. Hydraulic Engineering, ASCE,* **110**(2): 1755-1771.

Leutheusser, H.J. and **Schiller, E.J.** (1975) Hydraulic Jump in a Rough Channel, Water Power and Dam Construction, **27**(5): 186-191.

Mohamed Ali, H.S. (1991) Effect of Roughened Bed Stilling Basin on Length of Rectangular Hydraulic Jump, *J. Hydraulic Engineering, ASCE,* **117**(1): 83-93.

Negm, A.M. (1993) Relative Depth of Forced Free Hydraulic Jump, Proc. ICHE-93, *Advances in Hydro-science and Engineering,* **Sam S.Y. Wang (ed.),** Washington DC, USA, June 6-11, **I:** 1250-1256.

Negm, A.M., El-Tarzy, A.I., Abdellateef, M. and **Owais, T.M.** (1993a) Optimum Floor Length DS Hydraulic Structures With Staggered Roughness Elements, *Eng. Bulletin,* Faculty of Eng., Ain Shams University, Cairo, Egypt, **28**(1): 301-314.

Negm, A.M., Mowafy, M.H. and **Waheed ELdin, U.** (1993b) Relative Sequent Depth of Free Hydraulic Jump Downstream Hydraulic structures, ICMPSE-93, University of Alex., Alex., Egypt, April 26-29 : 415-425

Negm, A.M., Eisa, S.A. and **Waheed Eldin, U.** (1993c) The Most Efficient Roughness Pattern for Dissipating the Energy Downstream Hydraulic Structures, Proc. ICHE-93, *Advances in Hydro-science and Engineering,* **Sam S.Y. Wang (ed.),** Washington DC, USA, June 6-11, **1:** 943-949

Negm, A.M., Saad, M.B., Abdellateef, M., and **Owais, T.M.** (1994) Effect of Strip Roughness Shape on the floor length of the hydraulic structures, 19th Int. Conf. for Statistic, Computer Science, Scientific and Social Applications, 9-14 April 1994, *Eng. Science, Cairo,* Egypt, **1:** 107-127.

Ohtsu, I., Yasuda, Y. and **Yamanaka, Y.** (1991) Drag on Vertical Sill of Forced Jump, *J. Hydraulic Research,* **29**(1): 29-47.

Rajaratnam, N. (1968) Hydraulic Jumps on Rough Beds, *Trans. Eng. Inst.* Canada, **11**(A-2): May.

Ranga Raju, K.G., Kitaal, M.K., Verma, M.S. and **Ganeshan, V.R.** (1980) Analysis of Flow Over Baffle Blocks and End Sills, *J. Hydraulic Research,* **18**(3): 227-241.

Visher, D.L. and **Hager, W.H.** (1995) *Energy Dissipators,* IAHR Hydraulic Structures Design Manual Series, No. 9, Balkema, A.A. Publishers, Rotterdam, The Netherlands.

USBR (1958) Hydrualic Design of Stilling Basins and Bucket Energy Dissipators, *Engineering Monograph* No. 25, Denver, Col. USA.

(Received 05/06/1997;
in revised form 03/04/1999)

تأثير إرتفاع الخشونة على أداء أحواض التهدئة

عبد العظيم نجم[١] إيهاب وفائي[٢] و عبد العزيز العثمان[٣]

[١] قسم المياه والمنشآت المائية - كلية الهندسة - جامعة الزقازيق - الزقازيق - مصر
[٢] قسم الهندسة المدنية - كلية الهندسة والتكنولوجيا بالمطرية - جامعة حلوان - حلوان - مصر
[٣] قسم الهندسة المدنية - كلية الهندسة - جامعة الملك سعود
ص .ب (٨٠٠) - الرياض ١١٤٢١ - المملكة العربية السعودية

تقدم هذه الدراسة نتائج التجارب على تأثير إرتفاع الخشونة على أداء أحواض التهدئة . لقد أخذ طول القفزة كمؤشر رئيس على طول الحوض . أجريت التجارب المعملية على قناة صناعية واسعة لتقليل آثار الجدران الجانبية . توصل البحث إلى صيغ تجريبية عديمة الأبعاد لحساب طول القفزة الهدروليكية بدلالة نسبة إرتفاع الخشونة ورقم فرود عند بداية القفزة كما قدم البحث منحنيات ومعادلات للتصميم لتستخدم في التطبيقات الحقلية .