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Investigation of the Perfect Hydraulic Jump in Horizontal Rectangular Channel

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ABSTRACT

Accelerating the process of transition from supercritical to subcritical flow, by formation a forced hydraulic jump at the contract section (Forced perfect hydraulic jump), is one of the most important measures, in decreasing flow velocity, water energy dissipation and alleviation the scouring problem, leading to lessening the required protection length against the erosion issues in the bed of downstream of the channel. In the current study, physical model was prepared precisely at fluid mechanics laboratory in the faculty of Engineering/Alkhums at Elmergib University. Comprehensive experiments were conducted to evaluate measured and calculated characteristics of the perfect free jump, and consequently, the existence of the perfect hydraulic jump is investigated. Eventually, equation was derived that might be used to guarantee the existence of a free perfect jump, which is the limiting condition between both repelled and drowned jumps as well as, the limiting condition between both repelled and drowned jumps was graphically found.

Keywords

Hydraulic structure.

Water energy dissipation.

Perfect hydraulic jump.

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1 INTRODUCTION

1.1 Hydraulic jump and water energy dissipation

Studying hydraulic jump issues started to raise after the early 19th century. The hydraulic jump was connected with the Momentum Principle by Belanger in 1828. experiments were carried out by researchers and results showed excellent verification of the Momentum Principle in the hydraulic jump [1]. Whenever the flow profile changes from supercritical to subcritical, standing wave is formed which is called hydraulic jump. As a result, the water surface in the channel abruptly raised, turbulent water zone is generated, resulting in formation of surface rollers with intensive water mixing and air entrainment, accompanied by dissipation of a huge amount of water energy [2]. Hydraulic jump might be

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categorized in two types in regarding to characteristics of their bed, the first one is a classical hydraulic jump with smooth bed, and the other type is a forced hydraulic jump. The type of classical hydraulic jump has been widely studied by many researchers [3,4].

1.2 Hydraulic structure and the hydraulic jump

Hydraulic structures are commonly constructed in streams of erodible bed materials, or soil of fine particles and easy to transport due to flowing water, such as silt and clay. In the events of heavy rainfall, massive amount of surplus water might be released from the reservoir within a short space of time, through weirs, spillways and gates of the hydraulic structures, producing flow of high velocity. Accordingly, supercritical flow of high turbulent zone is generated, downstream the channel, immediately behind the toe of the hydraulic structure, causes a bed shear stress, resulting in, significant increase in sediments movement downstream of the hydraulic structure. consequently, the level bed of the channel in this zone becomes corroded and this is commonly known as local scour, as shown in Figure 1. Continuous erosion can deteriorate the foundation of the structure and maybe leading to the failure of the whole structure by time or in severe weather conditions [5].

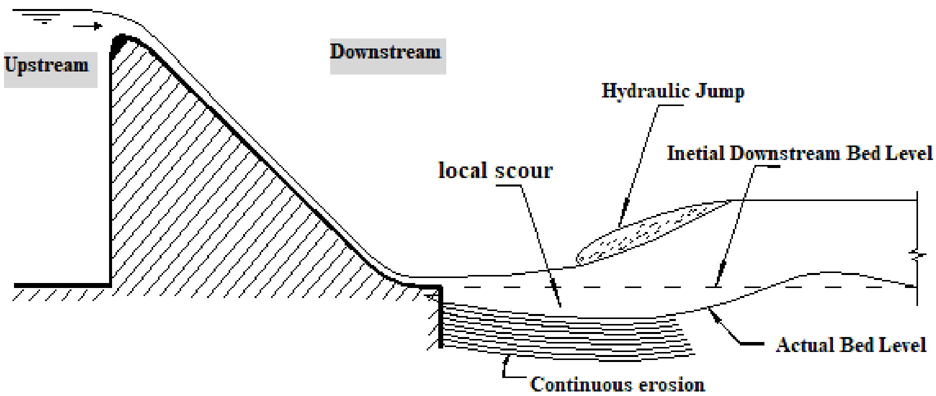

Figure 1. Continuous erosion process downstream a hydraulic structure.

2 MATERIALS AND METHODS

2.1 Experimental set-up

The experiments were performed at fluid mechanics laboratory in the faculty of Engineering/Alkhums at Elmergib University. The model was installed, and the experiments were conducted specially for studying the parameters involved in counter flow dissipator on the formed jump, considering the three cases; Free perfect jump, forced perfect jump and drowned jump, as shown in Figure 2 [6].

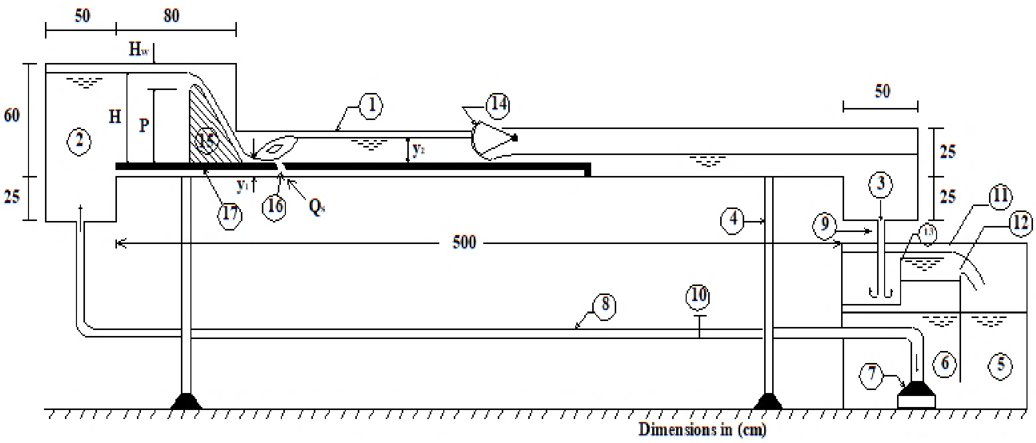

Figure 2. Schematic drawing of the experimental set-up.

The numbered accessories of the experimental setup may be described in details as following:

(1) Testing flume, (2) Inlet tank, (3) Discharge tank, (4) Pedestal, (5) Service module, (6) Sump tank, (7) Submersible pump, (8) Supplying pipe, (9) Discharge pipe, (10) Control valve, (11) Moulded channel, (12) Rectangular weir, (13) Screen, (14) Control gate, (15) Spillway model, (16) Slot and (17) structure floor.

2.2 Experimental investigation in characteristics of the perfect free jump

Different values of discharges flowing over the spillway crest were tested; Q_W = 500, 1000, 1500, 2000 and 2500 cm^3/sec, and the five corresponding values of the headwater depths; H = 45.7, 46.98, 48.05, 48.98 and 49.85 cm, respectively. Utilizing the tailgate in the flume, the formed hydraulic jump can be forced to move towards the toe of the spillway and located at the contracted section. In this case, the formed hydraulic jump is called perfect one ($y_1 = y_c$). The sequent depths y_1 and y_2, as well as the length L_J of the formed jump were measured. The required measured and calculated data are depicted in table 1 and 2, respectively, where the characteristics of the free perfect hydraulic jump condition are described.

Table 1. Measured data of the perfect free jump.

H cm	Q_W cm^3/sec	H_w cm	x_c cm	L_J cm	y_1 cm	y_2 cm
45.70	500	2.20	3.00	23.00	0.29	5.00
46.98	1000	3.48	5.32	35.00	0.50	7.50
48.05	1500	4.55	8.25	45.00	0.73	9.60
48.98	2000	5.48	11.00	53.00	0.94	11.25
49.85	2500	6.35	13.50	61.00	1.13	12.75

Table 2. Calculated data of the perfect free jump.

Q_W cm^3/sec	v_1 cm/sec	v_2 cm/sec	F_1	F_2	y_2/y_1	L_J/y_1	E_1 cm	E_2 cm	E_L/y_1
500	226.86	13.16	13.45	0.19	17.24	79.31	26.52	5.09	73.91
1000	263.16	17.54	11.88	0.20	15.00	70.00	35.80	7.66	56.28
1500	270.37	20.56	10.10	0.21	13.15	61.64	37.99	9.82	38.59
2000	279.96	23.39	9.22	0.22	11.97	56.38	40.89	11.53	31.23
2500	291.10	25.80	8.74	0.23	11.28	53.98	44.32	13.09	27.64

3 RESULTS AND DISCUSSION

3.1 Limiting condition of a free perfect hydraulic jump

As mentioned above, a free hydraulic jump is called perfect one when the front of jump lies immediately at the contracted section downstream the toe of weir ($y_1 = y_c$). In the case of free perfect jump, the initial depth of jump y_1 equals the contracted depth y_c, while the conjugate depth y_2 equals the tailwater depth y_D, as shown in Figure 3.

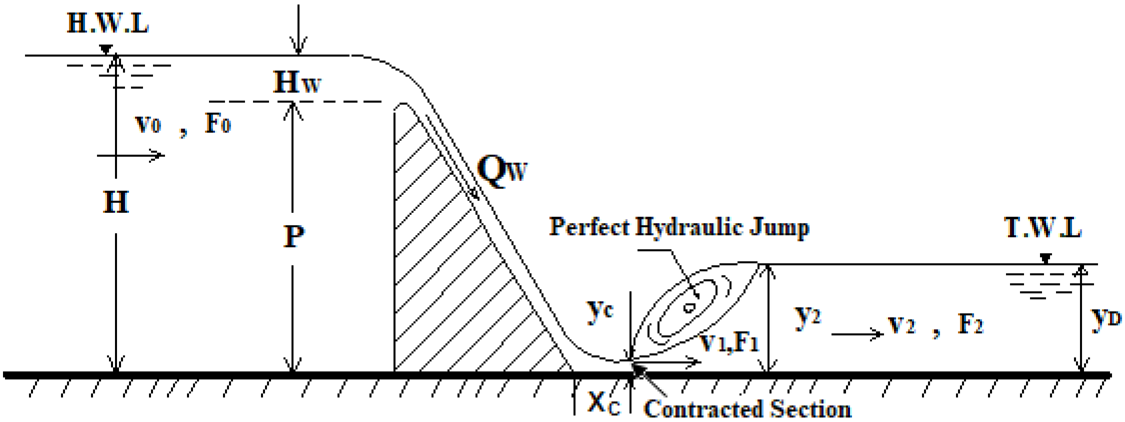

Figure 3. Definition sketch of the free perfect hydraulic jump.

To guarantee the formation of the free perfect jump, the head / tailwater depth ratio H/y_2 have to have a certain value, such a value might be assessed as follows:

The discharge passing through the contracted section Q_W, may expressed as:

$$Q_W = By_1C_v\sqrt{2g(H-y_1)} \tag{1}$$

where C_v is the velocity coefficient and B is the channel width.

The velocity of the headwater approach v_0 may be found as: $v_0 = \frac{Q_W}{BH}$.

Consequently, Froude number F_0, is given as: $F_0 = \frac{Q_W}{B\sqrt{gH^3}}$ or $Q_W = F_0B\sqrt{gH^3}$.

Substituting for Q_W in equation (1), yields: $F_0B\sqrt{2gH^3} = By_1\sqrt{2g(H-y_1)}^3$ (2)

From which: $\left(\frac{H}{y_1}\right)^3 - \frac{2C_v{}^2}{F_0^2}\left(\frac{H}{y_1}\right) + \frac{2C_v{}^2}{F_0^2} = 0$ (3)

Equation (3) is a cubic equation in the form of; $\left(\frac{H}{y_1}\right)^3 - a\left(\frac{H}{y_1}\right) + b = 0$ (4)

Where: $a = -\left(\frac{2c_v^2}{F_0^2}\right)$ and $b = \frac{2c_v^2}{F_0^2}$. The three roots of the equation (4) can be found as:

$$\frac{H}{y_1} = 2\sqrt{-\left(\frac{a}{3}\right)}\cos\left[\frac{N+2k\pi}{3}\right] \tag{5}$$

where k = 0, 1, 2 and $N = \cos^{-1}\left[\frac{-b}{2(-a/3)^{3/2}}\right]$. For the free hydraulic jump;

$$\frac{y_1}{y_2} = \frac{1}{2}\left(\sqrt{1+8F_2^2} - 1\right) \tag{6}$$

where F_2 is Froude number for the tailwater, $F_2 = \frac{Q_W}{B\sqrt{gy_2^3}}$ (7)

From equations (2) and (7);

$F_2 = F_0\left(\frac{H}{y_2}\right)^{3/2}$. Substituting for F_2 in equation (6), yields:

$$\frac{y_1}{y_2} = \frac{1}{2}\left(\sqrt{1+8F_0^2(H/y_2)^3} - 1\right) \tag{8}$$

Multiplying equation (5) by equation (8), gives:

$$\frac{H}{y_2} = \left(\sqrt{1+8F_0^2(H/y_2)^3} - 1\right)\sqrt{\left(\frac{-a}{3}\right)}\cos\left[\frac{N+2k\pi}{3}\right] \tag{9}$$

3.2 Condition of a free perfect hydraulic jump

As stated, the head / tailwater depth ratio H/y_2, that guarantee the existence of a free perfect jump, may be found from equation (9). The experimental measurements were used to verify equation (9), as shown in Table 3 and Figure 4. Comparison of results showed a good agreement between experimental and calculated values of H/y_2 with a maximum deviation of about 6%.

Table 3. Experimental and calculated values of the depth ratio.

F_0	Values of H/y_2		% Dev.
	Exp.	Cal.	
0.004	9.14	9.65	-5.60
0.013	6.26	6.34	-1.30
0.019	5.01	5.18	-3.40
0.025	4.35	4.54	-4.37
0.030	3.91	3.97	-1.50

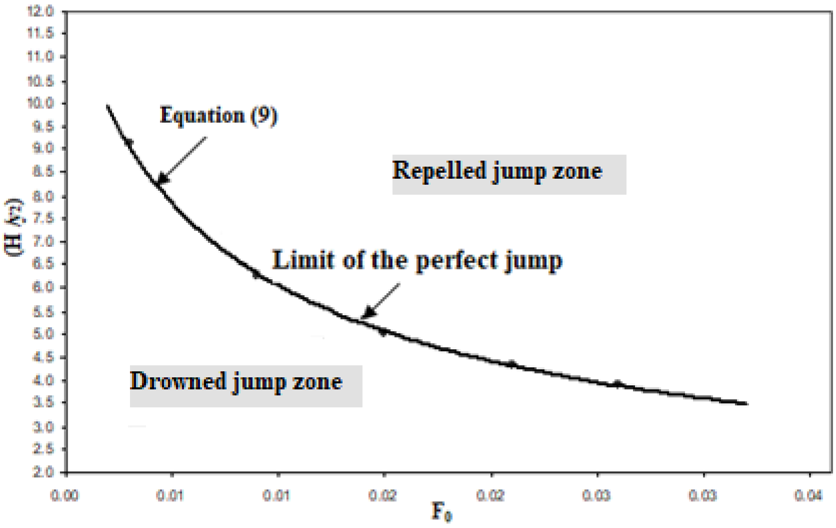

Figure 4. Comparison between experimental and calculated values of (H/y_2).

4 CONCLUSION

The free perfect jump is that jump condition which separates between both repelled and drowned jumps. The values of H/y_2 calculated from equation (9), will guarantee the existence of a free perfect jump, which is the limiting condition between both repelled and drowned jumps. Forcing the formed hydraulic jump downstream hydraulic structures as much as possible towards the toe of the structure is imperative, as it is in the case of the perfect hydraulic jump in the current study, resulting in, shortening the required length of downstream bed protection to a large extent and finally reducing the cost of construction. Therefore, verification of creation and existence of the perfect hydraulic jump is important matter in hydraulic structures field.

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استقصاء القفزة الهيدروليكية المثالية في قناة أفقية مستطيلة

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الملخص

تعدعملية تسريع التدفق أو جريان المياه في القنوات المفتوحة من التدفق فوق الحرج (Supercritical flow) إلى التدفق دون الحرج (Subcritical flow)، وذلك من خلال تشكيل قفزة هيدروليكية قسرية (Forced perfect hydraulic jump)، أحد أهم التدابير التي يُلجأ إليها لتشكيل القفزة الهيدروليكية في مكان قريب من السد أو المفيض أو أي منشأة الهيدوليكية. هذا الإجراء يساعد بشكل كبير في تخفيض سرعة التدفق وتبديد طاقة المياه المتدفقة، وبالتالي تقليل المسافة المطلوب حمايتها لتلافي مشكلة النحر و التآكل في قاع مصب القناة. في هذه الدراسة تم إعداد نموذج يحاكي الواقع والذي تم تصميمه بدقة بحيث نتحصل على نتائج يمكن الإعتماد عليها في الواقع. تم تصميم وتنفيذ هذا النموذج في معمل ميكانيكا الموائع بكلية الهندسة/ الخمس بجامعة المرقب. تم إجراء تجارب شاملة لتقييم الخصائص المقاسة والمحسوبة للقفزة الحرة المثالية (perfect free jump)، وبالتالي تم التحقق من تشكثل قفزة هيدروليكية قسرية مثالية (perfect hydraulic jump). في النهاية، تم إشتقاق المعادلة التي يمكن استخدامها لضمان وجود قفزة مثالية حرة ، وهي الحالة الفاصلة بين القفزة الهيدروليكية المطرودة (repelled jump) والمغمورة (drowned jump) ، حيث تم تمثيلها أيضاً بالرسم البياني.

الكلمات الدالة:
المنشأة الهيدروليكية
تبديد طاقة المياه
القفزة الهيدروليكية المثالية

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