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THE FRICTION RESISTANCE EFFECT ON THE HYDRAULIC JUMP LOCATION AND ENERGY DISSIPATION, A LABORATORY STUDY

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ABSTRACT

The location of the jump downstream the hydraulic structures outlets is an important parameter taken into considerations within the construction of the downstream protection works. One of the ways of moving the jump into a closer distance from the outlets is to raise the tail water level. In this research, a flow partitioning structure, FPS, designed, carried out, and installed downstream a sluice gate to apportion the cross sectional area of the flow and, then, increase the resistance of the friction force by increasing the walls of flow. The FPS shaped as a sectioned triangular prism consists of sets of 2.6cm×2.6cm iron square-section pipes formed with direction of the flow. The FPS with a vertical front face consisting of 16×11, rows × columns, of pipes extended 10cm downstream and held by a 0.5cm, thickness, iron bars and welded together to prevent any egression of the pipes from the FPS. This combination of the pipes and bars made a width of 29.6cm and height of 42.6cm to fit, approximately, the flume cross sectional area dimensions. The downstream face made with an inclination of 45^o to prevent the free fall of the water.

The system (which consists of a sluice gate, FPS, and rising weir) installed in a horizontal flume of 0.3m width, 0.45m depth, and 15m length. The system operated with flow rates ranged from 11.11 to 36.24l/s with different gate openings in 27 tests. In each test, the hydraulic jump formed downstream the sluice gate and the FPS once placed downstream the jump and once removed, in the same test, with maintaining the same flow conditions, and measurements are taken to investigate the effect of the FPS on the jump.

The results show that the additional friction resistance by the FPS increased the tail water level and forced the hydraulic jump towards the sluice gate, in which the FPS produced a converging distance ranged from 0.64m to 5.34m. This convergence of the jump lowered the head losses of the flow before the jump and then increased Froude Number, Fr, and produced higher y_2/y_1 value. The increased value of y_2/y_1 increased the energy dissipation of the jump, in which the jump produced energy dissipation ranged from 8.47 to 85.38% with the existence of the FPS instead of 5.91 to 66.14% without it, with same flow conditions. In spite of the considerable increase in the tail water level downstream the FPS, there was no significant differences of the dissipated energy with and without the FPS for the whole system, in which the energy dissipation ranged from 14.05 to 55.91% with the FPS and ranged from 13.57 to 55.09% without it.

KEYWORDS:

Hydraulic jump, Flow partitioning structure, Converging distance, Energy dissipation.

تأثير مقاومة الاحتكاك على موقع القفزة الهيدروليكية وكفاءة تشتيتها للطاقة، دراسة مختبريه

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الخلاصة

يعتبر موقع القفزة خلف منافذ تصريف المنشآت الهيدروليكية من العوامل المهمة التي تؤخذ بنظر الاعتبار في تصميم أعمال الحماية خلف تلك المنافذ. واحد طرق تقديم موقع القفزة إلى مسافة اقرب للمنافذ هو رفع منسوب الماء الذيلي في القناة. في هذا البحث تم تصميم منشأ تقسيم جريان ومن ثم نفذ ونصب خلف بوابة لتقسيم مساحة مقطع الجريان , والذي بدوره رفع مقدار مقاومة الاحتكاك بسبب زيادة مساحة التماس للجدران مع الماء. تم تنفيذ منشأ تقسيم الجريان على شكل موشور مثلثي مقطوع يتكون من مجموعة من أنابيب حديدية مربعة مساحة مقطعها بأبعاد 2.6سم × 2.6سم و وضعت باتجاه الجريان. يتكون منشأ التقسيم من وجه أمامي عمودي يتكون من 16×11 (سطر×عمود) من الأنابيب امتدت 10 سم الى الخلف ومسكت بقضيب سمكه 0.5 سم ليلتف حول الأنابيب ومن ثم تم لحم الأنابيب سويتا لزيادة تماسكها. هذه التشكيلة من الأنابيب والقضيب الماسك لها كان بعرض 29.6 سم وارتفاع 42.6 سم (والذي كان مقاربا لعرض وارتفاع القناة المختبرية). أما الوجه الخلفي للمنشأ فقد تم إمالته بزاوية مقدارها 45^{o} لمنع حدوث السقوط الحر للمياه.

تم تنصيب النظام الذي يتكون من البوابة ومنشأ تقسيم الجريان وسد غاطس متغير الارتفاع في قناة أفقية بعرض 0.3 م وارتفاع 0.45 م وطول مقداره 15 م. ومن ثم شغل هذا النظام بتصاريف تراوح مقدارها من 11.11 إلى 36.24 لتر\ثانية , وبفتحات مختلفة للبوابة خلال 27 تجربة. في كل تجربة تم إحداث قفزة هيدروليكية خلف البوابة , وقد تم استخدام منشأ التقسيم خلف القفزة مرة ورفعه مرة أخرى (بنفس التجربة) , مع الإبقاء على نفس خواص الجريان بالحالتين. خلال التجربة الواحدة (بحالتيها) تم اخذ نفس القياسات لبيان تأثير منشأ التقسيم على القفزة.

بينت نتائج البحث بان زيادة مقاومة الاحتكاك الإضافية بسبب منشأ التقسيم قد رفعت منسوب الماء الذيلي. وبسبب رفع منسوب الماء الذيلي تم دفع موقع القفزة إلى الأمام باتجاه البوابة بمسافة تزحيف تراوحت ما بين 0.64 و 5.34م. هذا التقريب للقفزة قلل خسائر الجهد قبل موقع القفزة , وبالتالي زاد من قيمة رقم فراود وأنتج قيمة أعلى ل y_2/y_1 . وهذه الزيادة في y_2/y_1 بالتالي أدت إلى زيادة تشتيت القفزة للطاقة. حيث أن القفزة أنتجت كفاءة تشتيت للطاقة تراوحت ما بين 8.47 و 85.38% بسبب وجود منشأ تقسيم الجريان. في حين أن الطاقة التي شتتها القفزة قد تراوحت ما بين 5.91 إلى 66.14% من دون وجود المنشأ وتحت نفس ظروف الجريان.

على الرغم من الزيادة الواضحة في منسوب الماء الذيلي خلف منشأ تقسيم الجريان , فلم يكن هنالك فرق واضح في مقدار الطاقة المشتتة الكلية للنظام ككل مع وجود أو عدم وجود منشأ تقسيم الجريان. حيث أن مقدار الطاقة الكلية المشتتة تراوحت مابين 14.05 و 55.91% بوجود المنشأ ومن 13.57 إلى 55.09% من دونه , وتحت نفس ظروف الجريان.

1. INTRODUCTION

Usually, the outlets of the hydraulic structures discharging water in supercritical condition accompanied with high velocity and high energy. This high velocity and energy of the flow represents an effective parameter taken into consideration in construction of the downstream protection works; because, the flow could cause a severe damage of the channel downstream the outlets. Many researchers conducted lot of energy dissipaters, such as increasing the roughness of the spillways by a set of steps to reduce the out flow energy within the structure. Others, used stilling basins with different layouts and appurtenances like chute blocks, baffle blocks, and end sills; Bradly and Peterka, 1957; Fiala and Albertson, 1961; Keim, 1962; Flammer, et. al, 1970; Garde, et al., 1986; Goel and Verma, 1999; Goel, 2007; Tiwari, 2013a and 2013b;Tiwari and Tiwari, 2013; and Tiwari et.al, 2011, 2013, 2014; and many others, to retard the flow of water and reduce the energy or produce a hydraulic jump to work as an energy dissipater. The jump within these structures dissipates the initial energy with a reduction may attain 85%; Chow, 1959.

The hydraulic jump is that phenomena where the flow changes from a high velocity condition, supercritical flow, to a lower velocity condition, subcritical flow, relatively within a short distance accompanied with energy dissipation. Chow defined the hydraulic jump as a wave, its shape depending upon the initial depth and Fr, and its location depending upon the tail water depth; Chow, 1959; and, may be a stationary or moving jump; Chanson, 2009. This phenomena take place in a location where the sequent depths of the jump satisfy the momentum equation of Belanger; Rajaratnam and Subramanya, 1966; Jeppson, 1970; Rajaratnam and Murahari, 1971; and Hager and Bremen, 1989. Therefore, the length of the downstream protection works must contain the jump position to ensure no scour occurrence of the channel bed, because the jump produces huge turbulences.

The hydraulic jump type stilling basins work to increase the tail water level with the act of the end sills to increase the energy dissipation of the hydraulic jump. Also, raising the tail water level moves the location of the jump upstream to a close distance from the toe of the hydraulic structure. Subsequently, this action reduces the cost of the construction of the downstream apron.

The end sills, in most designs, produce a stagnation zone at the back side or at front and back sides, depending upon the sill shape. This stagnation zone causes a sedimentation zone which accumulates sediments carried by the water, or produced by the scouring action. Also, the end sills disturb the flow and make turbulences that scour the channel bed and sides.

The objectives of this research are:

1. Increasing the tail water level downstream the hydraulic jump by increasing the channel friction resistance using a facility that does not produce a stagnation zone, or sedimentation zone, and
2. Investigating the effect of this modification on the location and energy dissipation of the jump.

2. MATERIALS AND METHODS

This part describes the way of producing a facility that increasing the friction resistance of the flume downstream the hydraulic jump, the design and carrying out of this facility, a comparison of this facility with some other shapes of sills, system installation and tests procedure, and the measurements that are carried out.

2.1. FPS Design and Carrying Out

To investigate the effect of increasing the flume friction resistance on the location and energy dissipation of the hydraulic jump, a partitioning of the cross sectional area of a part of the flume made downstream the hydraulic jump. This partitioning produced using a flow partitioning structure, designed with a triangular prism-shape using a combination of pipes installed with direction of flow to partition the flow into small streams through the FPS. This partitioning of flow increases the friction resistance by the pipes material and increases the retardation of the front face of the FPS to the flow. Fig. 1 shows an elementary profile of the FPS with a vertical front face of 30cm width (to befit with the flume width), 42cm height (approximately befit the flume depth), and an inclined downstream face with 45^{o} (to prevent waves occurrence by water free fall from the FPS).

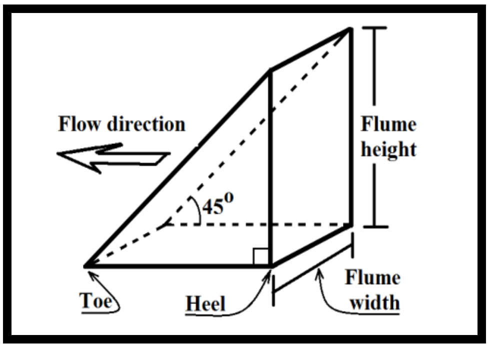
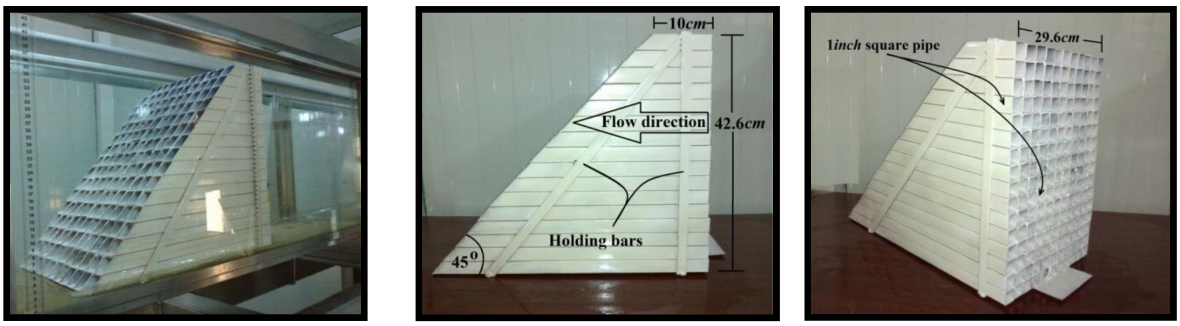


Fig. 1. An elementary profile of the FPS

The flow partitioning structure carried out using sets of 2.6cm×2.6cm, outside dimensions, iron square-section pipes roughen than the flume material formed with direction of the flow to make a sectioned triangular prism, as shown in Fig. 2. The front face of the FPS formed by 16×11, rows× columns, of pipes surrounded by bars with thickness of 0.5cm , to hold the pipes, making net width × height of 29.6cm × 42.6cm. And, the FPS extended 10cm to produce a space for the bars that holding the FPS. In addition to the bars, the pipes welded together to prevent the pipes egress from the FPS by the water during operation.

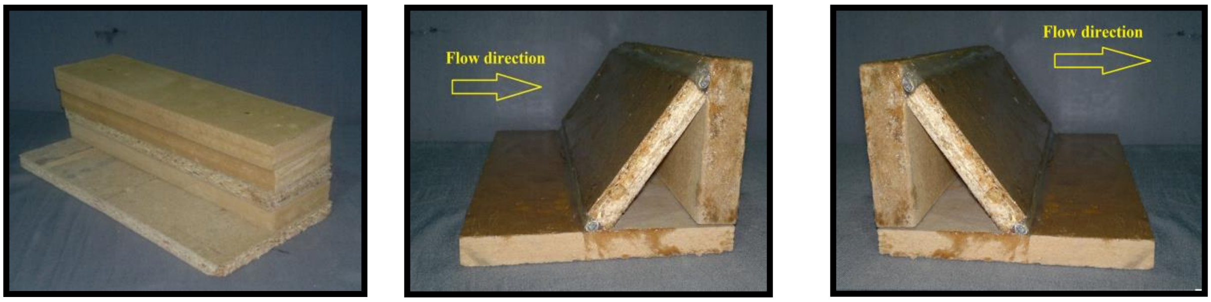


a- Downstream side of FPS **b- Side view of FPS** **c- Upstream side of FPS**

Fig. 2. The flow partitioning structure

2.2. FPS Comparison with Sill

A comparison of FPS with some shapes of sills carried out to investigate the stagnation zone and turbulences that could occur at one or both sides of the FPS. The shapes of sills that used in this manner were rectangular and triangular shapes. These shapes of sills fabricate with no specific criteria of design. The triangular shaped sill placed in two directions; once the vertical side facing the flow and the other facing the inclined side with the flow, as shown in Fig. 3.



a- Rectangular sill **b- Triangular sill with inclined front face** **c- Triangular sill with vertical front face**

Fig. 3. Different cases of sills

2.3. System Installation and Operation

A flume of 0.3*m* width, 0.45*cm* depth, and 15*m* length placed horizontally (to prevent the effect of gravity) used for this manner. The flume provided by a sluice gate placed at the upstream side of the flume to produce the hydraulic jump and a rising weir placed at the end of the flume to control the tail water level. The flume is part of Laboratory of Hydraulics of the Department of Structures and Water Resources Engineering, Faculty of Engineering, University of Kufa.

The flow partitioning structure placed downstream the sluice gate with a distance of 10m, for all the tests, to maintain the occurrence of the hydraulic jump between the gate and the FPS, as shown in Fig. 4. Then, the rising weir placed downstream the FPS to control the location of the jump.

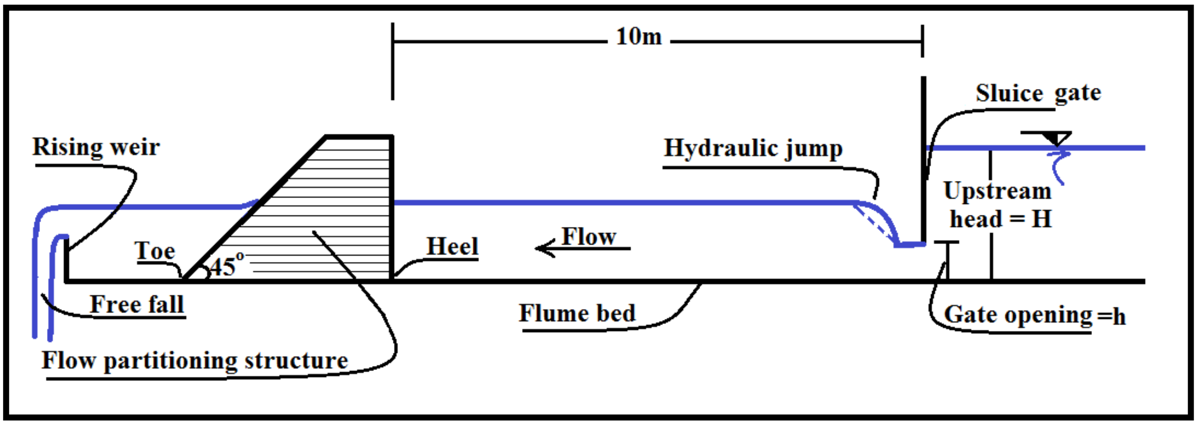


Fig. 4. The layout of the system installation

The system operated with and without the FPS, with remaining the same flow conditions, to investigate the effect of the FPS on the location of the hydraulic jump and energy dissipation. The operation of the system summarized in the following items:

1. The flume operated in a $Q=Q_1$l/s (Max. flume discharge) and the gate opened in a certain opening (h=h1cm, Max. gate opening),
2. The FPS placed 10m downstream the gate,
3. The weir raised to increase the tail water level and forcing the jump into a very close position from the upstream gate,

4. Measurements are taken,
5. In the same discharge ($Q=Q_1$l/s), gate opening ($h=h_1$cm), and weir level (i.e. all the system conditions are the same), the FPS removed from the system and the same measurements are taken again, to investigate the effect of the FPS on the measured parameters,
6. The items 1 to 5 repeated with same discharge ($Q=Q_1$l/s), but different gate openings ($h=h_2$, h_3, …, hncm) till the minimum gate opening,
7. The items 1 to 6 repeated with different discharges ($Q=Q_2$, Q_3… Q_nl/s) till the minimum flume discharge.

The weir height depending upon the hydraulic jump position from the gate with the existence of the FPS; and, the gate opening depending on the following:

1. Maximum gate opening (h=Max. hcm) depending on the minimum Fr, Fr>1, which produces an obvious hydraulic jump,
2. Minimum gate opening (h=Min. hcm) depending on the maximum upstream head (Max. Hcm) which does not makes the flume flood, at the upstream side of the sluice gate.

2.4. Flow Measurements and Calculations

The measurements that carried out during the system operation with the existence of the FPS were the flume discharge, sluice gate opening (hcm), sequent depths of the jump (y_1 and $y_2$cm), water depth at the heel ($y_3$cm) and toe position of the FPS ($y_4$cm), and the distance from the gate to the beginning of the jump. These measured parameters repeated again with the removal of the FPS with remaining all the system conditions in the same.

The system operated with flow rates ranged from 11.11 to 36.24l/s with different gate openings in 27 tests, as illustrated in Table 1. This table presents the test number, discharges, gate opening, and the corresponding Fr under the gate to insure super critical flow under the upstream gate. The test number represents the operation of the system in both cases, with and without FPS.

Table 1. The operated flowrates, gate openings, and the corresponding F_r.

Test No.	Q, l/s	Gate opening, cm	Fr under the gate
1	36.24	8*	1.70
2	36.24	6.5	2.33
3	36.24	5#	3.45
4	32.58	7.5*	1.69
5	32.58	6.5	2.09
6	32.58	5#	3.10
7	29.25	7*	1.68
8	29.25	6	2.12
9	29.25	5	2.78
10	29.25	4.2#	3.62
11	26.05	6.2*	1.80
12	26.05	5.5	2.15
13	26.05	4.5	2.90
14	26.05	3.8#	3.74
15	22.11	5.5*	1.82
16	22.11	4.5	2.47
17	22.11	3.5#	3.59
18	18.42	4.8*	1.86
19	18.42	4	2.45
20	18.42	3.2	3.42
21	18.42	2.5#	4.96
22	14.82	4*	1.97
23	14.82	3	3.04
24	14.82	2.1#	5.18
25	11.11	3.4*	1.89
26	11.11	2.5	2.99
27	11.11	1.7#	5.34
Max.	36.24	8	5.34
Min.	11.11	1.7	1.68

Notes: * Maximum gate opening.

- # Minimum gate opening.

The calculations that carried out are the converging distance of the jump from the upstream sluice gate by the act of the FPS, Fr of the initial depth of the jump, and energy dissipation of the hydraulic jump and the whole system (i.e. the energy dissipated from gate to the toe of the

FPS). The converging distance calculated by subtracting the distance between the jump and the gate with the existence of the FPS from the same distance without the FPS.

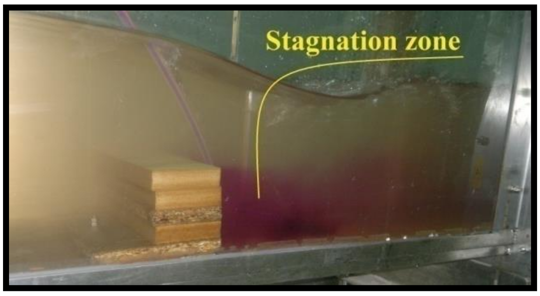
3. RESULTS AND DISCUSSIONS

This part presents the results of the FPS comparison with the three cases of the sill, discussions of the changes in water depths by the FPS along the system, and their effect on the characteristics of the hydraulic jump.

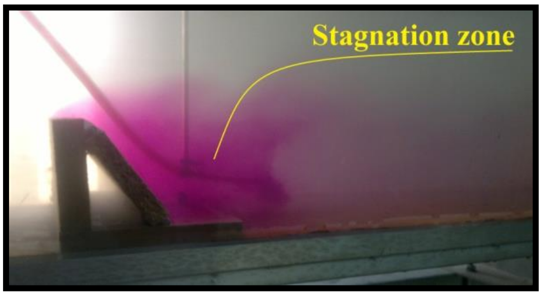
3.1. The stagnation zone

As the cross sectional area of flow partitioned by the act of FPS, the flow maintained, approximately, with no interference between the partitioned streams, as shown in Fig. 5. This non-interference action produced by the FPS pipes and the inclination of its downstream side. Fig. 5, also, shows that the three cases of the sills produced stagnation zones at both sides or one side, while no stagnation zone produced with the FPS.

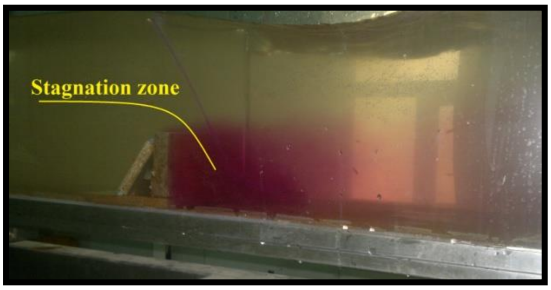
Namely, the FPS produced no turbulences that increase the scouring, and no sedimentation zone that accumulates the transported silts with the water. Or, the FPS reduced the protection and the dredging works of the channel at the structure position.



a- The rectangular shape



b- The triangular shape



c- The reversed-rectangular shape

d- FPS upstream side

e- FPS downstream side

Fig. 5. Stagnation zones

3.2. Water Depths in the System

Since the flow partitioning structure increased the adjacent surface area, walls, to the flowing water, subsequently, the friction resistance increased. This increase of friction resistance reduced the flow velocity and, then, increased the water level of the flow at the heel of the FPS, as shown in Fig. 6. This figure shows that the water level at the heel position with the existence of the FPS was higher than that with absence of it.

At the downstream position of the FPS the tail water level reduced by the completion of the FPS friction resistance, as shown in Fig. 7.

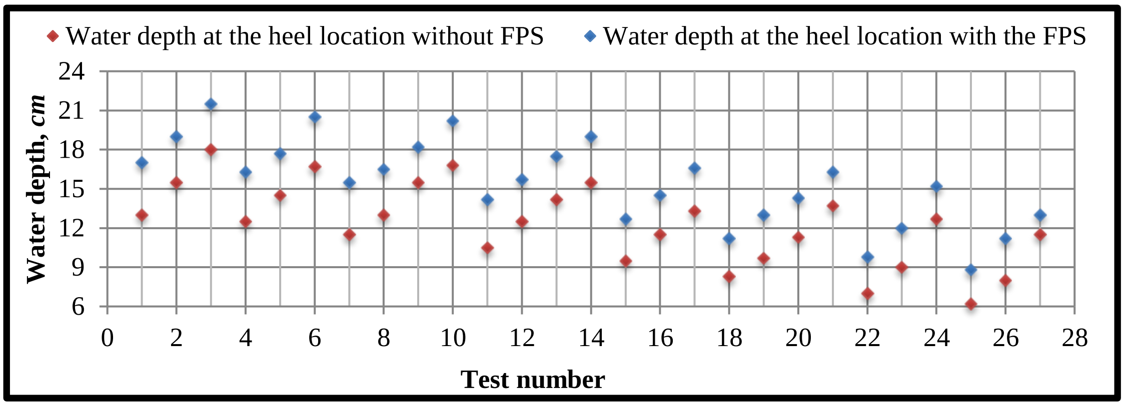


Fig. 6. Increase of water depth at the heel position by the FPS

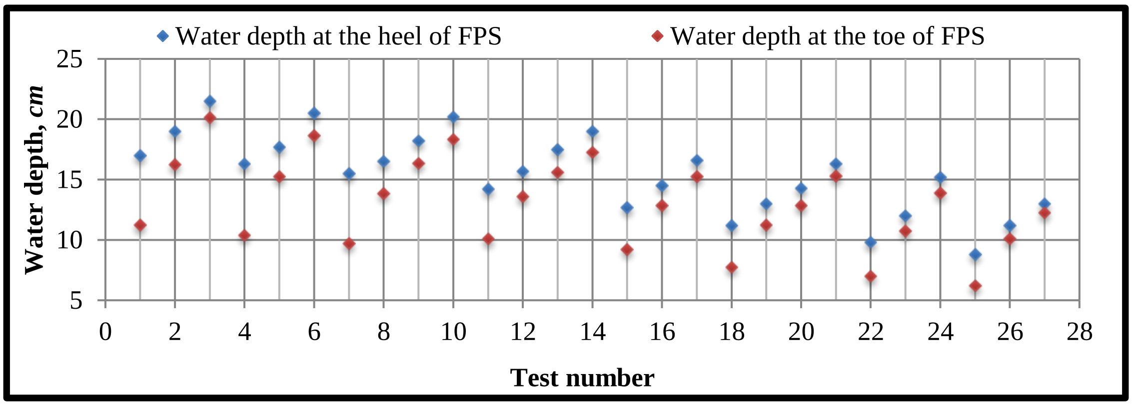


Fig. 7. Reduction of water level at the toe position of FPS

The downstream inclined face of the structure assisted in maintaining the reduction of the water level within a gradual decrease, as shown in Fig. 8. This figure shows two cases of water level reduction; one with high tail water level (by the act of the raising the downstream weir); and the other with low tail water level. The action of gradual reduction prevented the free fall of water that perhaps scour the downstream reach of the channel.

a- **Head difference with raising the downstream weir**

b- **Head difference without raising the downstream weir**

Fig. 8. Gradual reduction of water depth downstream the FPS

3.3. Location of the Hydraulic Jump

By the act of the raised water level at the upstream side of the FPS, at heel, the hydraulic jump moved upstream towards the sluice gate, as shown in Fig. 9. This figure shows that the converging distance of the jump by the act of FPS decreases with the increase of Fr under the gate.

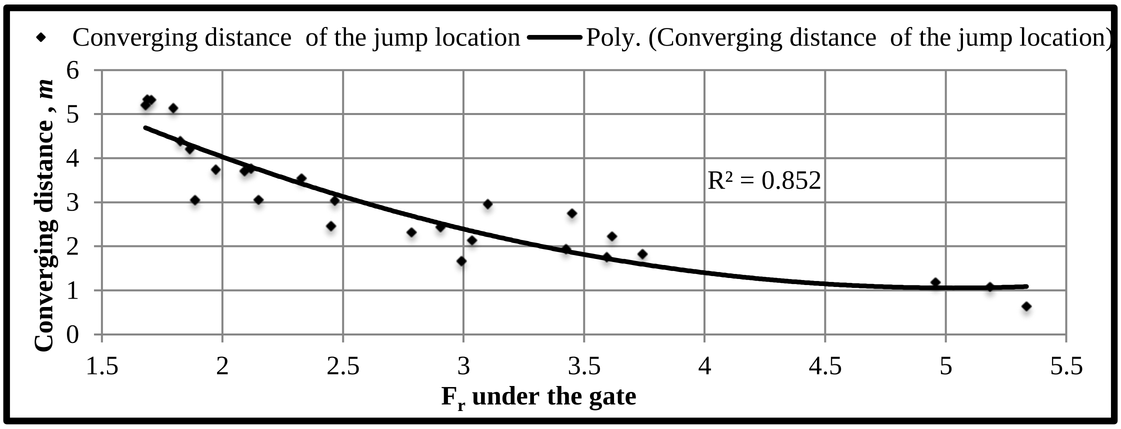


Fig. 9. Converging distance of the jump location

The decrease of converging distance with increase of Fr referred to the increase of y_2/y_1, as shown in Fig. 10, and to the decrease of initial depth of the jump, as shown in Fig. 11. These two figures, also, show that the initial depth of the jump with the FPS is lower than that without it; and, y_2/y_1 of the jump with the FPS is higher than that without it. This is referred to the location of the jump, in which as the jump moves downstream as the losses of energy increase, and then, the initial depth of the jump, also, increases. Namely, the jump with the FPS moved upstream (lower losses); and, the jump without the FPS moved downstream (higher losses). Also, the sequent depth with the FPS was higher than that without it. The FPS produced a converging distance ranged from 0.64m (with Fr of 5.33) to 5.34m (with Fr of 1.69).

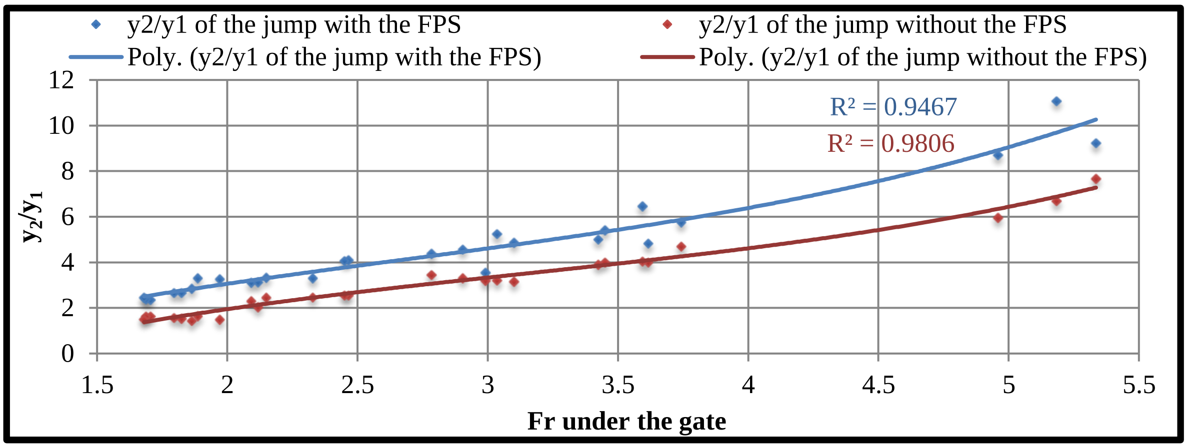


Fig. 10. y_2/y_1 of the jump with and without FPS

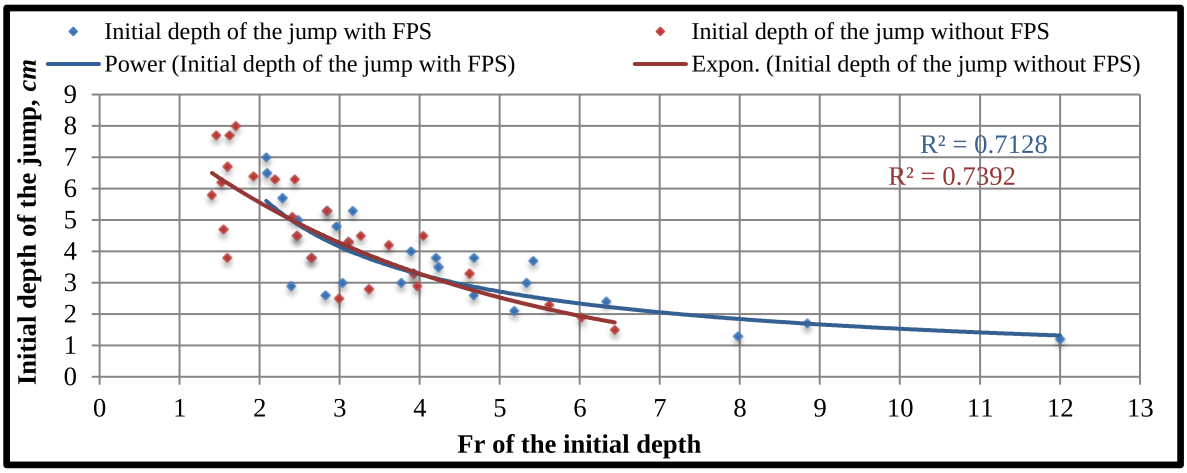


Fig. 11. Initial depth of the jump with and without FPS

The higher ratio of y_2/y_1 with the FPS than that without it is referred to the higher values of Fr with the FPS than that without it, as shown in Fig. 12. In which the reduction of the initial depth of the jump within the same flow rates produced this difference.

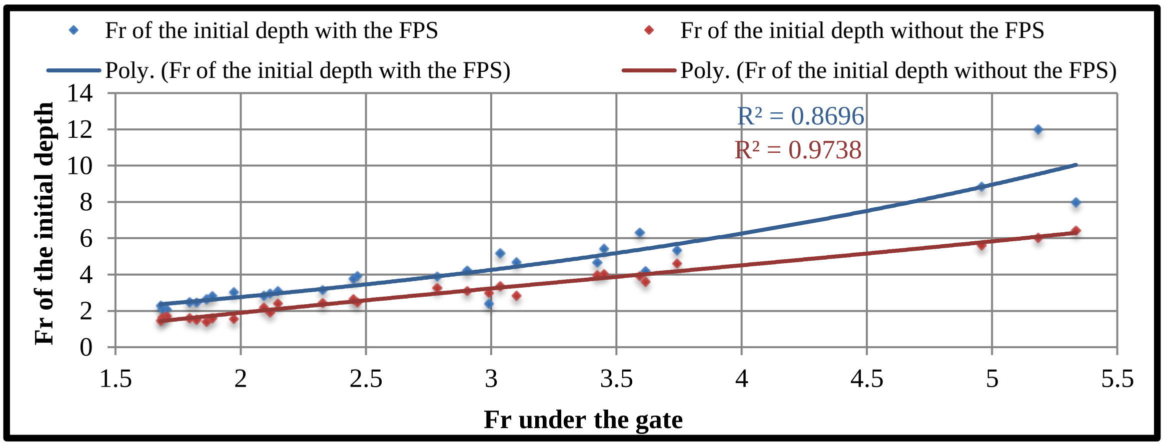


Fig. 12. Fr of the Initial depth of the jump with and without FPS

3.4. Energy Dissipation

As presented, since the water depths by the act of the FPS are raised, as a result, the velocity of flow also decreased. This change of flow characteristics influenced the energy dissipation of the hydraulic jump and the whole system. Fig. 13 shows that the energy dissipation produced by the jump with the FPS was higher than that without it, within the same test. The results recorded an energy dissipation of the jump with the FPS ranged from 8.47 to 85.38%, and ranged from 5.91 to 66.14% without it. This is ascribed to the change of y_2/y_2, as presented before, in which the energy dissipation of the jump depending upon the initial and sequent depths, Chow, 1959; Wu and Rajaratnam, 1995.

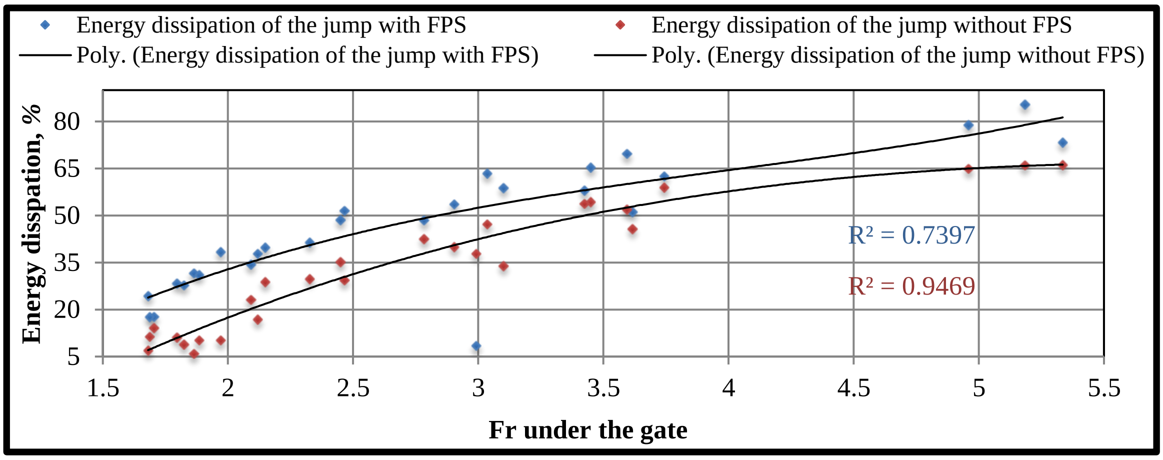


Fig. 13. Energy dissipation of the jump with and without FPS

According to the results that recorded for the system energy dissipation, as shown in Fig. 14, in spite of this change of the flow characteristics, the energy of the flow had no significant changes along the experimental work. The recorded system energy dissipation was ranging from 14.05 to 55.91% with the FPS and ranging from 13.57 to 55.09% without it.

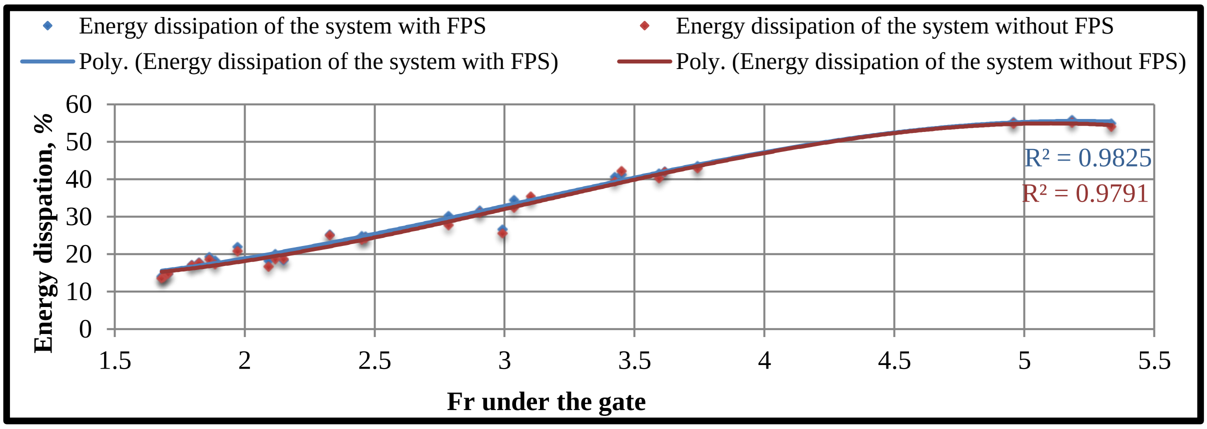


Fig. 14. Energy dissipation of the system with and without FPS

4. CONCLUSION

The flow partitioning structure produced a retardation force by the act of increasing the friction resistance that raised the tail water depth downstream the jump. This action forced the hydraulic jump to move upstream and increased its energy dissipation. The following conclusions deduced from the operation of the system:

1. The FPS produced no stagnation zone that accumulates sediments and no turbulences that scouring the channel.
2. The friction resistance, by the FPS, increased the water level of the flow at the heel of the FPS.

3. By the act of the raised water level at the upstream side of the FPS, at the heel, the hydraulic jump moved towards the upstream sluice gate.
4. The initial depth of the jump with the FPS was lower than that without it; and, y_2/y_1 of the jump with the FPS was higher than that without it.
5. The FPS produced a converging distance ranged from 0.64m (with Fr of 5.33) to 5.34m (with Fr of 1.69).
6. The energy dissipation produced by the jump with the FPS was higher than that without it, in the same test; in which the energy dissipation of the jump with the FPS ranged from 8.47 to 85.38%, and ranged from 5.91 to 66.14% without it.
7. The total energy of the flow for the system had no significant changes along the experimental work; in which the recorded system energy dissipation ranged from 14.05 to 55.91% with the FPS and ranging from 13.57 to 55.09% without it.

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