The effect of the obstacle on the hydraulic response of the composite hydraulic structure

Rafi M. QASIM[1], Ihsan A. ABDULHUSSEIN*[,1], Alya A. MOHAMMED[1], Qusay A. MAATOOQ[1]

*Corresponding author
[1]Southern Technical University/ Basra Engineering Technical College, Basrah, Iraq,
Drengihssan@stu.edu.iq

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Abstract: *Experimental investigations are carried out to study the physics of the flow that passes weir-gate hydraulic structure and encounters obstruction with or without installation of downstream opening. This study approaches the comparison between two different options; the first option deals with free flow condition while the second option deals with submerged flow condition. Various cases are performed considering different hydraulics variables and dimensions variables to evaluate the existence of obstruction with or without openings. Overall the flow pattern is more sensitive to the presence of obstruction at downstream region than in its absence. The hydraulic variables that are considered in the study are divided into dimensional variables such as discharge, downstream flow velocity and water depths at downstream and non-dimensional variables such as discharge coefficient, Froude number and Reynolds number. The obstacles which are used in this study have variable heights with constant width and length. Constant spacing between the obstacles is adopted. Different arrangements of obstacles are considered in this study and it is found that a significant and reasonable result is different among the cases. The effect of rectangular opening in the obstruction on flow pattern is studied. The effect of obstacles with rectangular opening gives a noticeable result in the assessment of the discharge coefficient of the composite hydraulic structure.*

Key Words: *Composite structure, free and submerged flow condition, gate, obstacle, weir*

1. INTRODUCTION

Water management in open channel by using composite hydraulic structure represents a reasonable method to control, divert and distribute the required quantity of water especially in the irrigation system. The advantage of using a composite hydraulic structure is represented by removing floating material by a weir and removing the accumulation of deposited material by a gate with high efficiency. When the water flow in river and channel passes an obstacle such as block, dike, pier, debris material or boundary roughness energy losses could occur and as a result, the water level around obstacle would be different. This condition must be considered by hydraulic engineers. The interaction between the composite hydraulic structure and the channel water flow has not been investigated under the consideration of obstacles at downstream regime of channel in previous works. Reference [1] investigated the influence of insertion holes located at the middle of obstacles. The study adopted different obstacles configurations in a channel with constant Reynolds number depending on obstacles height.

The Ansys software was utilized to solve the problem based on the finite volume method. The variables such as velocity profile, streamlines averaged time, drag coefficient and turbulence kinetic energy were considered in their study. Reference [2] investigated the flow field influences on prismatic obstacles in three dimensions considering different widths. They used various flow visualization techniques such as crystal violet, laser visualization and oil film. Also, the static pressure is measured at constant value of the Reynolds number based on the height of cube. They took in consideration the profile of velocity, streamlines and data of the pressure coefficient. The flow in_channel around a cubic obstacle of certain height was numerically investigated by [3]. In their study, they examined two turbulence models of (Large Eddy Simulation) LES and (Reynolds –averaged Navier Stock equations) RANS and compared them with the experimental result obtained from [2], where the Reynolds number is equal to the constant value depending on the obstacle height. They concluded that the (RANS) turbulence model is overestimated. The effects of block element on a hydraulic jumps where studied by [4]. From the experimental works they found that the boundary layers would develop faster and the dimensions of jump would decrease considerably. Reference [5] measured the coefficients of resistance of the circular vertical cylinders in a rectangular channel. However, they did not consider the differences in the water level which occurred by the cylinders. On other hand, reference [6] implemented a two-dimensional model for the flow passing a vertical plate; they proved that an eddy viscosity model which is calculated from friction velocity can gives a satisfactory prediction of the velocity field. On the other hand, reference [7] studied the impact of obstacles, in the shape of a quarter cylinder, on the hydraulic jump in a channel with a rectangular section. The diameters of the quarter-cylindrical obstacles are 2 and 3 cm and the influence of their height and location is investigated in the hydraulic jump variables such as energy dissipation, Froude number and location. The location of the obstacles is at the end of the channel. The distance between the channel beginning and the first obstacle was constant. The study indicated that when the distance increases among the obstacles to a specific quantity, the energy dissipation increases. The rate of increase in the energy dissipation starts to decrease as the distance among the obstacles keeps on increasing beyond that specific quantity. Reference [8] investigated the influence of the distance between continued walls on the bed on controlling hydraulic jump.

They showed that increasing in the wall height had a reducing role of secondary depth and the length of whirlpool jump. Reference [9] investigated the interaction between the flexible and flow plants that covered the riverbed. Experimental run and measurements of the flow turbulence in open channel containing plastic plants seeded in gravel bed were investigated. The resistance of flow due to roughness of flexible vegetation for different densities of plants was attained. A dramatic relationship was found between the flow field velocity and the height of deflected plants.

The aim of the present work is to study the flow characteristics when it crosses the composite weir – gate structure and encounters obstacles located at downstream of hydraulic regime provided with or without rectangular opening shape.

2. FLUID MECHANICS BASICS

The theoretical value of flow-rate (Q_{theor}) that passes the composite weir-gate hydraulic structure is described by the combination of both weir flow-rate (Q_{weir}) and gate flow-rate (Q_{gate}) as given in the equation below:

$$Q_{theor} = Q_{weir} + Q_{gate} \tag{1}$$

The following equation is used to obtain the theoretical flow-rate that passes the rectangular weir [10]:

$$Q_{weir} = \frac{2}{3}\sqrt{2g}Lh^{3/2} \tag{2}$$

The continuity equation is used to obtain the theoretical flow-rate through gate, [10].

$$Q = V.A \tag{3}$$

$$Q_{gate} = V.A_g = \sqrt{2gH}\,A_g \tag{4}$$

For free flow condition

$$H = d + y + h \tag{5}$$

For submerged flow condition

$$H = d + y + h - h_d \tag{6}$$

$$Q_{act} = C_d Q_{theor} \tag{7}$$

$$Q_{act} = C_d\left[\frac{2}{3}\sqrt{2g}Lh^{3/2} + \sqrt{2gH}A_g\right] \tag{8}$$

where: Q_{theor} is theoretical discharge, Q_{act} is actual discharge, C_d is discharge coefficient, H is upstream water depth, d is depth of water at the gate opening, h is water head at sharp crest weir, g is gravity due to acceleration, V is water flow velocity, y is vertical distance between weir and gate, h_d is downstream water depth, L is rectangular notch width, A_g is flow cross sectional area at the gate opening.

The Froude Number and Reynolds Number are determined using the following equations (9) ([11]), and (10) ([12]), respectively:

$$F_r = \frac{V}{\sqrt{gy}} \tag{9}$$

$$R_e = \frac{Vh_d}{\nu} \tag{10}$$

where: ν is water kinematic viscosity.

3. EXPERIMENTAL WORK

A series of experiments runs were carried out at flume with rectangular cross section. The dimension of the flume is (7.5cm) width, (15cm) height and (2m) long. The flow-rate is measured by using the volume method, while the depth of water is measured by using point gage scales.

Composite weir-gate structure models are made by using a sheet of wood with (5mm) thickness bevelled along all the edges at (45°) with sharp edges of thickness (1mm) [13]. The obstacles models with or without openings are made by using wood of thickness (1cm), while the dimensions of rectangular opening are (3.5cm × 1cm). The spacing between obstacles is (10cm).

Three different heights of obstacles are used in this work (2, 3 and 4cm) regardless the presence of opening.

Four different arrangement of obstacles are adopted in this work regardless the existing of opening.

The first obstacles are located at distance (30cm) at downstream regime measured from composite hydraulic structure. The weir-gate structure is fixed to flume by using Plexiglas supports.

The following procedures were used in laboratory run:

1- The flume is always in horizontal position.
2- The weir-gate structure was fixed into flume at distance (80cm) from the beginning of the flume.
3- Submerged flow condition is satisfied due to the presence of obstacles with or without opening.

The above procedure is repeated for all tests (runs). In each run, weir-gate flow-rate, water head of weir, water depth at downstream regime and water depth at upstream regime, are measured under free and submerged flow condition.

Figure (1) shows the details of the composite hydraulic structure. Figure (2) shows the location of the composite hydraulic structure and the arrangement of obstacles which are considered in the present study.

Also, table (1) illustrates the input data and table (2) shows the selected output information from the current work.

The main target of the present work refers to study the flow characteristics when it crosses the composite weir – gate structure and encounters obstacles located at downstream of hydraulic regime.

This paper represents a challenge in the assessment of the workability of weir – gate hydraulic structure under the influence of obstacles. Three different conditions are considered in this study.

A: weir – gate structure without consideration of obstacle.

B: weir – gate structure with consideration of obstacle.

C: weir – gate structure with consideration of obstacle but the obstacle contains a rectangular opening of dimension (3.5cm x 1cm).

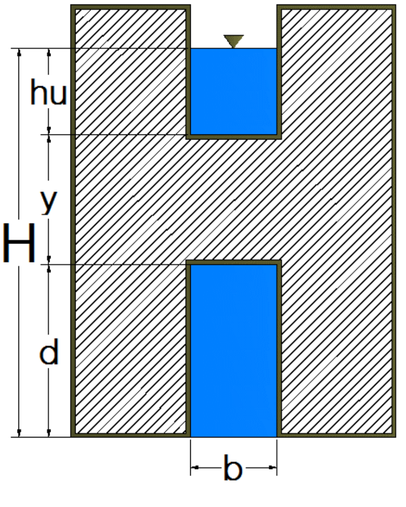


Figure 1. Details of composite hydraulic structure

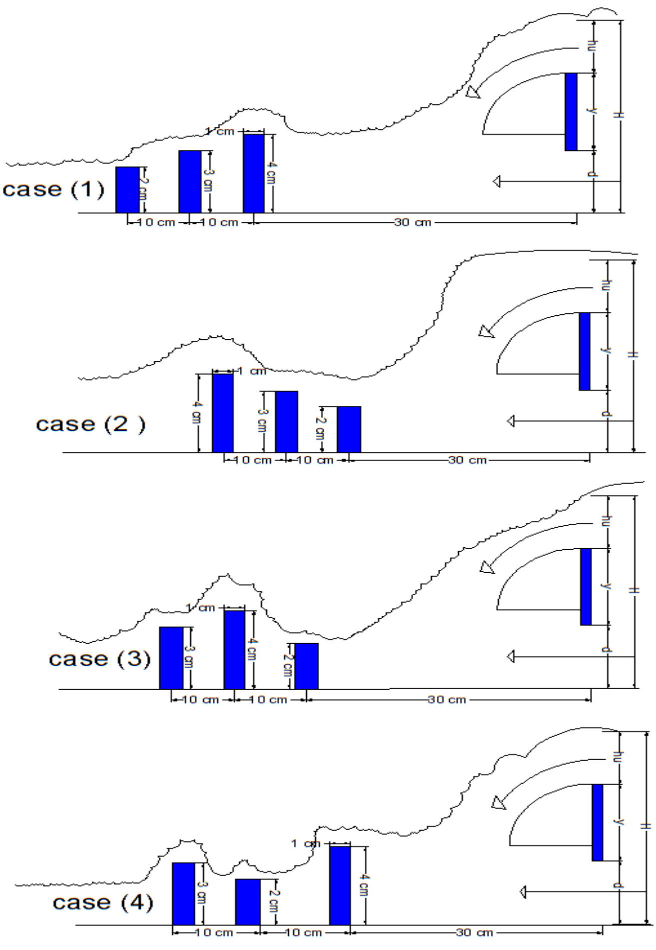


Figure 2. Arrangements of obstacle downstream composite rectangular weir-gate structure

Table 1. The Dimensions and Details of Weir-Gate Hydraulic Structure.

Model No.	hu (cm)	y (cm)	d (cm)	H (cm)
1	3	2	4	9
2	2	2	4	8
3	1	2	4	7
4	3	3	3	9
5	2	3	3	8
6	1	3	3	7
7	3	4	2	9
8	2	4	2	8
9	1	4	2	7
10	3	4	2	9
11	2	4	2	8
12	1	4	2	7

Table 2. The Selected Results that was Estimated from Experimental Run Performed in Laboratory.

Model Case	h_d (cm)	Fr_{down}	Fr_{up}	R_N	V (m/s)	Q_{actual} (L/s)	$Q_{theor.}$ (L/s)	C_d
1(B1)	4.80	0.312	0.121	10292	0.214	0.771	1.550	0.498
2(C1)	4.50	0.397	0.156	11047	0.245	0.828	1.240	0.665
3(C1)	3.42	0.394	0.134	7812	0.228	0.586	0.838	0.695

4(B2)	5.26	0.286	0.127	10820	0.208	0.811	1.498	0.659
5(B2)	4.80	0.271	0.107	7290	0.150	0.546	1.207	0.567
6(C2)	4.57	0.218	0.145	6667	0.146	0.500	0.710	0.704
7(A)	1.60	1.514	0.113	9600	0.600	0.720	0.839	0.858
8(B3)	4.30	0.309	0.122	8651	0.201	0.684	1.344	0.509
9(C3)	3.64	0.255	0.095	5555	0.152	0.416	0.575	0.723
10(B4)	4.40	0.274	0.093	7941	0.180	0.595	0.686	0.867
11(C4)	3.36	0.275	0.075	5312	0.158	0.398	0.548	0.726
12(C4)	3.04	0.286	0.082	4761	0.156	0.357	0.411	0.867

4. RESULTS AND DISCUSSIONS

The obstacles in open channel and rivers have been considered by hydraulic engineers as a source of resistance to the stream flow, so to increase water conveyance gradually it should be eliminated or removed the obstacles from the path of the water flow.

The usual purpose of using the obstacles in the downstream hydraulic structures is to dissipate the energy.

Whereas, in this study the main aim of inserting obstacles at the downstream hydraulic structure is to raise the water level to the highest possible level in order to provide energy, thus pushing the water to the farthest possible downstream point.

This paper explains the noticeable interferences between obstacles which are considered as source of energy losses on hydraulic characteristics of weir-gate hydraulic structure which is operated according to the fundamental of interaction between over flow velocity and under flow velocity with high efficiency in removing of floating material by weir and accumulation of sediment material by gate.

Figure (3) shows the hydraulic behaviour between two non-dimensional parameters which are discharge coefficient and downstream Froude number for all cases of obstacles arrangement.

Basically, Froude number is classified into three types.

- Subcritical flow ($F_r < 1$) which leads to the occurrence of low flow velocity and the gravity force is prevalent.

-Supercritical flow ($F_r > 1$) which leads to the occurrence of high flow velocity and the inertia force is prevalent.

-Critical flow that occurs when($F_r = 1$) [14]. Figure (3) clearly shows that the value of the Froude number is changed by the value of the discharge coefficient. The inequality in distribution between the Froude number and the discharge coefficient depends on obstacles arrangement which is essential based on obstacle height taking into consideration that the width and length of the obstacle are considered fixed.

Also, the spacing between the obstacles is constant. In addition, the figure shows a variation in the Froude number values which leads to the change of the dominating force that controls the whole hydraulic regime (gravity and inertia). The results show that case-2 is better as compared with other cases.

This is because the maximum discharge coefficient value that is accumulated huge dense in range between (0.5-1) and this happen owing to the arrangement of obstacles. The feasible arrangement of obstacles from short to high (case-2) is likely to lead to an increase in the actual discharge quantity of supply water comprising the quantity of water passing through the openings and that part of the flow passing over the obstacles. The arrangement (case-2) will share in increase the actual discharge and this lead to increases the discharge coefficient due to direct proportional between them.

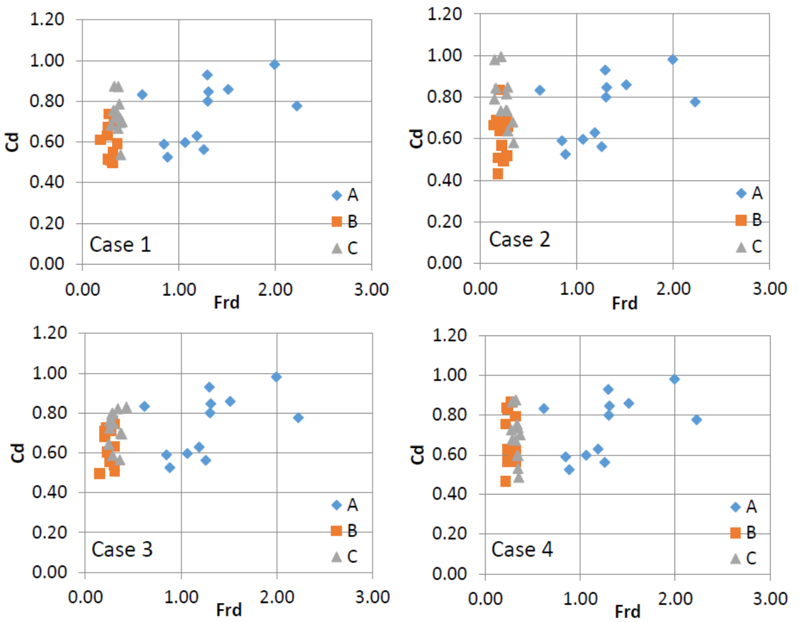
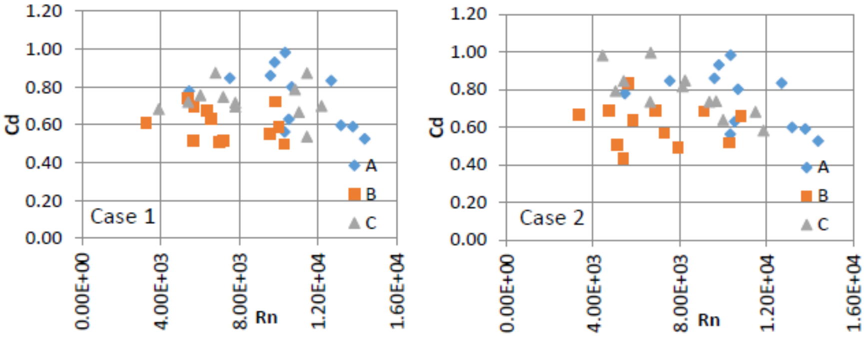


Figure 3. Relation between Discharge Coefficient and downstream Froud Number

Figure (4) shows the hydraulic behavior between two non-dimensional parameters, the discharge coefficient and the downstream Reynolds number for all cases of the obstacles arrangement. It is obvious from figure (4) that as the Reynolds number increases, the discharge coefficient decreases. This is due to the effect of water flow velocity which is shared on the interaction between the non-dimensional parameters discharge coefficient and the Reynolds number. The Reynolds number is directly proportional to the water flow velocity while the discharge coefficient is inversely proportional to the water flow velocity. So, this conflict will be reflected on the flow pattern or trend in the relationship between these parameters irrespective of the presence of obstacles. This figure implies that the presence of obstacles does not have any noticeable influence on pattern between the Reynolds number and the discharge coefficient. The actual (measured) discharge for free condition and a submerged flow condition are represented in comparison with the discharge coefficient of weir-gate structure as shown in figure (5). It is obvious that as the measured discharge increases the discharge coefficient increases for all options (A, B and C). This is due to the direct proportion between the actual discharge and the discharge coefficient. Again, the result showed that case-2 is better as compared to other cases and the effect of the obstacle containing an opening is more visible as compared to other cases.



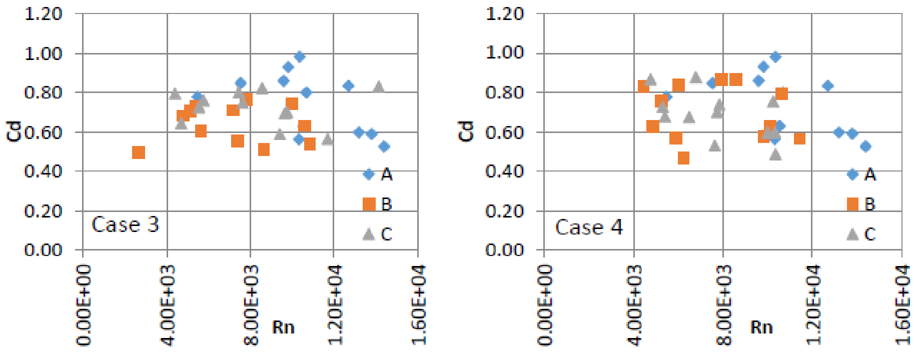


Figure 4. Relation between Discharge Coefficient and downstream Reynolds Number

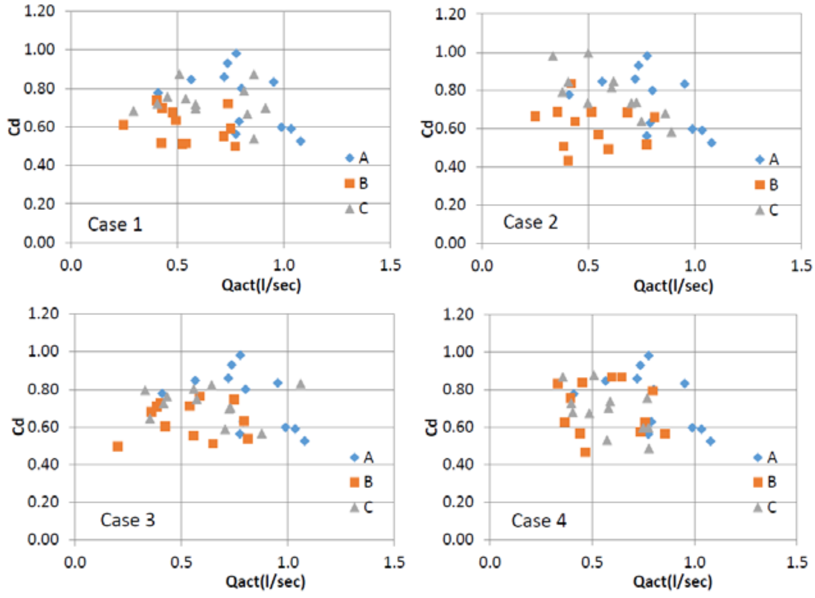


Figure 5. Relation between Discharge Coefficient and Measured Discharge

The pattern relationship between the discharge coefficient and the downstream water flow velocity of the regime is investigated as shown in figure (6). Generally, the discharge coefficient does not have any theoretical or empirical relationship with the water flow velocity at downstream regime. So, a complex random relationship may be described between both of them. The variance in relationship occurs due to the interaction between the factors that control the discharge coefficient and the water flow velocity at downstream regime. Basically, the discharge coefficient depends on the interaction between the over flow velocity and the under flow velocity, weir head, weir width, vertical distance between weir and gate, water depth at gate opening and width of gate; while water flow velocity at downstream regime depends on flow that passes weir-gate structure, number of obstacles, dimension of obstacles, spacing between obstacles, location of obstacles and arrangement of obstacles. Overall, these factors will be reflected on the relationship between both of them. It is clear from figure (6) that the discharge coefficient and water flow velocity at downstream regime increase moderately because both of them are based on water flow quantity at downstream regime. Case-2 is better as compared with other cases. It is clear from figure (6) that the pattern is distributed randomly for free flow condition (A) as compared to submerged flow condition (B and C) where the distribution can be considered dense accumulated with high intensity at specific range.

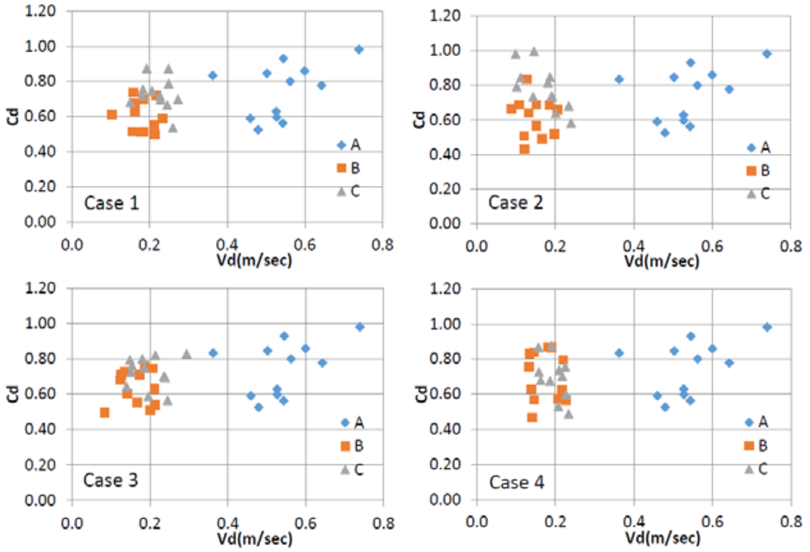


Figure 6. Relation between Discharge Coefficient and Velocity

Figure (7) shows the hydraulic behaviour between two non-dimensional parameters, the discharge coefficient and the upstream Froude number for the all cases of the obstacles arrangement. It is obvious from the figure that all cases have the same pattern relationship between the discharge coefficient and the upstream Froude number. The presence of obstacles in downstream regime does not have any noticeable effect on the relationship between them. Case-2 is better as compared with/to other cases regardless the number of obstacles, dimension of obstacles, spacing between obstacles, and location of obstacles and arrangement of obstacles in downstream regime. It is clear from figure (7) that the trend in relationship between the non-dimensional parameters in free flow condition (A) is not very different for all cases of obstacles arrangement. Also relationship between non-dimensional parameters for submerged flow condition (B and C) is not very different for all cases of obstacles arrangement. But the behaviour in free flow is not identical with submerged flow.

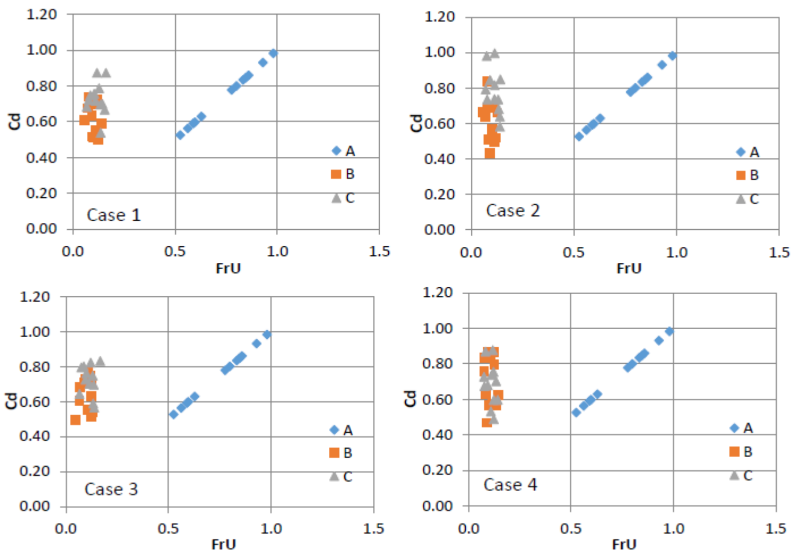


Figure 7. Relation between Discharge Coefficient and Upstream Froude Number

Figure (8) shows the relationship between the discharge coefficient and the average downstream water depth. It is clear from this figure that as average downstream water depth increases, the discharge coefficient decreases except case (2) because the effect of obstacle containing opening is more visible as compared to other cases. Basically, the discharge coefficient and the average downstream water depth are considered independent variables, so the flow velocity is adopted to distinguish between both of them. The discharge coefficient especially depends on the interaction between the over flow velocity and the under flow velocity while the average water depth at downstream regime depends especially on the flow velocity at downstream regime in the case without obstacles, while in the case of existing of obstacles it will depend on additional factors such as number, dimension, spacing, location, and arrangement of obstacles in downstream regime. So, all these factors will be reflected on the pattern of flow and will affect the relation between the discharge coefficient and the average downstream water depth. Table (3) shows the relationship between the flow properties and the area of opening for different cases and models. It is clear from the selected results shown in table (3) that as the ratio (A_O/BH) increases, the measured discharge decreases. In this work A_O is constant (A_O: represents the area of the rectangular opening) and B is constant (B: represents the flume width), so H is dominating on the actual discharge quantity ($H = h_u + y + d - h_d$) while H has major effect on the quantity of discharge that passes the composite structure but it has minor impact on the quantity/amount that passes the obstacles. The reduction in flow quantity at downstream occurs due to the interaction between the neighbouring obstacles where the spacing between them can be considered small, so these obstacles confined the quantity of water. Also, as the ratio (A_O/BH) increases the discharge coefficient must decrease due to direct proportion between the discharge coefficient and the actual discharge or due to inverse proportion between discharge coefficient and H. The fluctuation in results occurs due to the effect of obstacles on the interaction between the over flow rate from weir and the under flow rate from the gate. Also, as the ratio (A_O/BH) increases, the Reynolds number decreases. In general, the Reynolds number depends on the water flow velocity at downstream regime and on the average water depth at downstream regime. Also, as the ratio (A_O/BH) increases, the downstream Froude number decreases. In general, the Froude number depends on the water flow velocity and the average water depth at downstream regime. Any fluctuation occurring in values due to the presence of obstacles, especially arrangement of obstacles has a direct effect on the obtained values. In addition, the interaction between the over flow velocity and the under flow velocity will affect the obtained results.

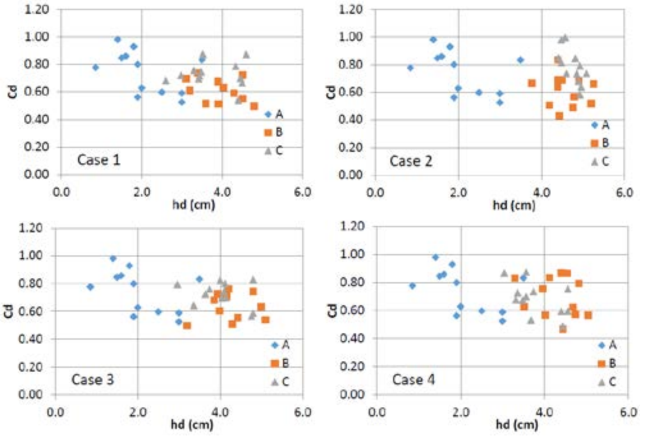


Figure 8. Relation between Discharge Coefficient and Average downstream Water Depth

Figure (9) shows the relationship between the water depths at downstream and the distance travelled by the water flow for different models considered, namely two cases (B and C) under submerged flow condition. For the cases of obstacles without opening the water depth starts from the highest point and then gradually drops with distance until it reaches least value. In cases of the obstacles with openings the water depth starts to rise until it reaches the maximum value and then drops to the least value. So, the variation or conflict in shape of water depths pattern is related to the number, dimension, spacing, location and arrangement of obstacles in downstream regime. So, all these factors will be reflected on the pattern of flow. Figure (9) shows moderate range of water depths between (1-8) cm with distance for both cases (B and C) and this represents a good features for the use of obstacles in downstream of hydraulic regime. Figure (10) shows a good comparison between two different cases. This comparison proves that the use of obstacles with openings in downstream regime of channel fortifies the composite structure workability because the height of water depth is always satisfactory as compared with/to the use of obstacles without openings.

Table 3. Variation of Flow Properties with Area of Opening

Case	Model	Ao/BH	Q_{act} (l/sec)	C_d	Rn	Fr_d
1	1	0.05185	0.85960	0.53714	11461	0.39648
1	2	0.05833	0.82873	0.66566	11050	0.36957
1	3	0.06667	0.58594	0.69517	7813	0.39438
1	4	0.05185	0.91463	0.69833	12195	0.41338
1	5	0.05833	0.85960	0.87212	11461	0.37091
1	6	0.06667	0.51020	0.87308	6803	0.32888
1	7	0.05185	0.81301	0.78625	10840	0.38279
1	8	0.05833	0.58594	0.71623	7813	0.39095
1	9	0.06667	0.45317	0.75554	6042	0.32181
1	10	0.05185	0.53957	0.74613	7194	0.35382
1	11	0.05833	0.40595	0.71975	5413	0.33594
1	12	0.06667	0.29412	0.68287	3922	0.29865
2	1	0.05185	0.8902	0.581029	11869	0.3458
2	2	0.05833	0.7500	0.637036	10000	0.2890
2	3	0.06667	0.6186	0.847157	8247	0.2843
2	4	0.05185	0.8621	0.679908	11494	0.3388
2	5	0.05833	0.7026	0.733645	9368	0.2797
2	6	0.06667	0.5000	0.994613	6667	0.2177
2	7	0.05185	0.7264	0.736624	9685	0.2696
2	8	0.05833	0.6098	0.814195	8130	0.2734
2	9	0.06667	0.4060	0.843683	5413	0.1634
2	10	0.05185	0.4975	0.733492	6633	0.2143
2	11	0.05833	0.3778	0.791131	5038	0.1470
2	12	0.06667	0.3333	0.979469	4444	0.1496
3	1	0.05185	0.87719	0.56418	11696	0.35957
3	2	0.05833	0.70588	0.58755	9412	0.28574
3	3	0.06667	0.57252	0.74599	7634	0.29357
3	4	0.05185	1.06007	0.82992	14134	0.42912
3	5	0.05833	0.72464	0.69418	9662	0.37989
3	6	0.06667	0.43228	0.76046	5764	0.25442
3	7	0.05185	0.73171	0.69938	9756	0.36978
3	8	0.05833	0.64240	0.82138	8565	0.34184
3	9	0.06667	0.41667	0.72370	5556	0.25541
3	10	0.05185	0.55866	0.80005	7449	0.28438
3	11	0.05833	0.35253	0.64248	4700	0.24366
3	12	0.06667	0.32967	0.79404	4396	0.27558
4	1	0.05185	0.77720	0.48716	10363	0.35364
4	2	0.05833	0.75000	0.59567	10000	0.34593

4	3	0.06667	0.58027	0.70083	7737	0.36776
4	4	0.05185	0.77519	0.59615	10336	0.33890
4	5	0.05833	0.57252	0.53053	7634	0.34524
4	6	0.06667	0.50934	0.87588	6791	0.32280
4	7	0.05185	0.76923	0.75391	10256	0.33629
4	8	0.05833	0.58824	0.73612	7843	0.34622
4	9	0.06667	0.40541	0.67746	5405	0.28529
4	10	0.05185	0.48701	0.67346	6494	0.31936
4	11	0.05833	0.39841	0.72609	5312	0.27537
4	12	0.06667	0.35714	0.86761	4762	0.28684

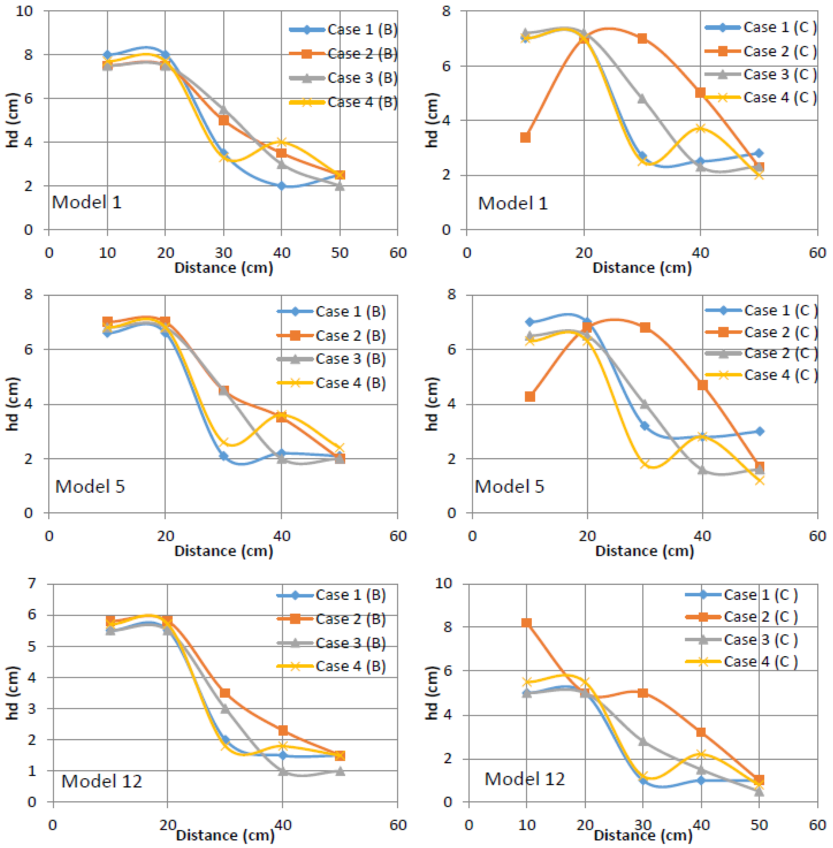


Figure 9. Downstream Water Depth Profile for different cases

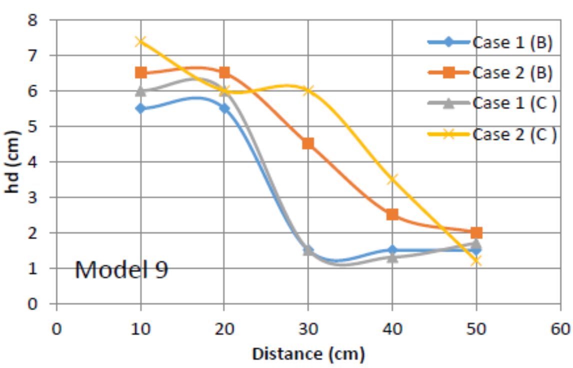


Figure 10. Comparison between Case (B) and (C) for downstream Water Depth Profile

In general, when the impact occurs between the obstacles and the water flow, a resistance force will generate and develop in obstacles and lead to flow momentum loss and this will reflect on hydraulic behaviour of the weir-gate structure. Also the presence of openings in obstacles reduces the resistance force and the flow momentum loss and this represents an important issue for hydraulic regime. The obstacles achieve two different jobs; the first one is related to the increase of the water level while the second is related to allowing water to pass through the openings in addition to the water, which passes over the obstacles.

5. CONCLUSIONS

The following significant points are obtained from the present paper:

1- Obstacles play a significant role in the assessment of the water depths in downstream of the channel and this will be reflected in the operation of the weir-gate hydraulic structure.
2- Among the obstacles dimensions (height, width and length) the height has major effect and this be reflected in the operation of the weir-gate hydraulic structure.
3- It is recommended to use obstacles with openings as compared with/to obstacles without openings due to the opening effect of on the flow characteristics.
4- The arrangement of obstacles has a noticeable role on the flow characteristics.
5- Area of openings has a significant influence on the hydraulic variables.
6- Obstacles have major effect on the relationship between the discharge coefficient and the Froude number at downstream regime as compared with/to the upstream of the hydraulic regime.
7- Obstacles have major effect on the relationship between the discharge coefficient and the Reynolds number.
8- The existence of obstacles in downstream region has reasonable effect on the discharge coefficient and the actual discharge.
9- The pattern which describes the relationship between discharge coefficient and water flow velocity at downstream regime of channel can be considered suitable.
10- Water depths at downstream regime will not have effect on the value of discharge coefficient.
11- The fluctuation in values of the Froude and Reynolds numbers will depend on factors that control the flow characteristics of the composite hydraulic structure and obstacles characteristics.
12- The obstacles produce a resistance force that leads to the flow momentum loss.

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