SUBMERGED FLOW CHARACTERISTICS IN A POOL-TYPE-STILLING BASIN WITH MULTI-END STEPS

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ABSTRACT

Stilling basins are in common use when designing heading-up hydraulic structures such as barrages, dams, weirs, …etc. Careful investigation of the flow characteristics and associated flow phenomena should be conducted before constructing such important and costly structures. During this phase, many scenarios are tested to conclude the basic features of the safe design and to suggest and test proposed solutions of the observed harmful flow-associated problems. Generally, the investigated flow characteristics may include the main parameters of the submerged hydraulic jump, the vertical velocity distribution along the bed, the velocity decay, and the stability of bed protection downstream the apron of the stilling basin. In the present research paper, these characteristics will be tested in a pool-type stilling basin with multi-end steps downstream (DS) Naga Hammadi Barrages physical model. The used flume had 1.0 m wide, 26.0 m long and 1.20 m deep. The results of the tested models were compared to conclude the optimal hydraulic design criterion. Each model was tested under 36 different flow conditions.

This extensive investigation revealed that the optimal design should satisfy the criteria $e/H_u=0.14$ and $k_2/H_u=0.14$ where e is the height of the pool at the inlet and k2 is the height of the pool at the outlet. The design will be optimal if it produces the shortest length of submerged hydraulic jump, faster decay of near-bed-velocity, shortest length from the gate to the section where the velocity distribution is fully developed, minimum scour dimensions DS of basin and hence the highest stability of bed protection.

Keywords: Barrages, physical model testing, stilling basin, flow characteristics, hydraulic jump, velocity distribution, bed protection and scour.

INTRODUCTION

Various Barrages have been built along the Nile River in order to regulate water distribution and control flows to maximize profitability and minimize losses, such as Esna, and Naga Hammadi Barrages by the Ministry of Water Resources and Irrigation (MWRI). During the testing of New Esna Barrage design and performance on a physical model, it was observed that the scour immediately downstream the stilling basin exceeded the expected values. This observation was verified further during the monitoring of the actual structure. The same findings were also observed during the design and model testing of New Naga Hammadi Barrages. In both cases, significant design modifications were introduced using trail and error process based on expert's opinion. Therefore, there is a need to develop and improve some design criteria for hydraulic structures to be used in future applications and suitable for the Nile River conditions.

Previous investigations on submerged hydraulic jumps and stilling basins are numerous, e.g. [1,10,11,12,21]. Also, many studies were interested in the investigation of scour and its control downstream hydraulic structures and specially stilling basins, e.g. [2,9,13,14,15,18,19,23,24]. Moreover, few studies involved measurements of velocity near bed during the different operations of multi-vents Barrages [17,19]. Some studies investigates the effect of using under-gate sill on free flow downstream gates, e.g. [4,20,21] and others on submerged flow downstream gates, e.g. [7,8,21] However, none of these studies were conducted on a Barrage physical model that represents the Nile River conditions. Only few studies dealing with physical models concerning Naga Hammadi Barrages are available [3,4,5]. Therefore, the present investigation comes on line to extend the previous limited number of investigations and to cover this serious gap to avoid future designs that based on trial and error of the stilling basins downstream the Nile River Barrages.

THEORETICAL BACKGROUND

Figure 1 shows the definition sketch for the submerged flow downstream of a radial gate with DS pool of equal inlet and outlet heights. Using the dimensional analysis, the following functional relationship was obtained between the relative length of the submerged hydraulic jump, L_{sj}/y_1, (y_1 is the depth at the vena contracta) and the other governing parameters.

$$\frac{Lsj}{y_1} = f\left(\frac{e}{Hu}, \frac{k_2}{H_u} \frac{h}{H_u}, \frac{y_t}{y_1}, F_{r1}\right) \tag{1}$$

in which: e/H_u is the relative inlet height at the beginning of the pool, k_2/H_u is the relative outlet height at the end of the pool, h/H_u is the relative differential head, y_t/y_1 is the relative tailwater depth or submergence and Fr_1 is the Froude number at the vena contracta. All tests were conducted under particular tailwater conditions. Therefore, y_t/y_1 is of minor importance due to the fact of being keeping it constant.

Similarly, the relationship concerning the relative near-bed-velocity, v_b/v_1, (v_1 is the velocity at the vena contracta) could be expressed as follows.

$$\frac{v_b}{v_1} = f\left(X, \frac{e}{Hu}, \frac{k_2}{H_u}, \frac{h}{H_u}, \frac{y_t}{y_1}, F_{r1}\right) \tag{2}$$

in which: X is the relative horizontal distance where the velocity is measured.

It should be noted that similar equations may be written for the relative maximum depth of scour and the relative energy loss of the submerged hydraulic jump.

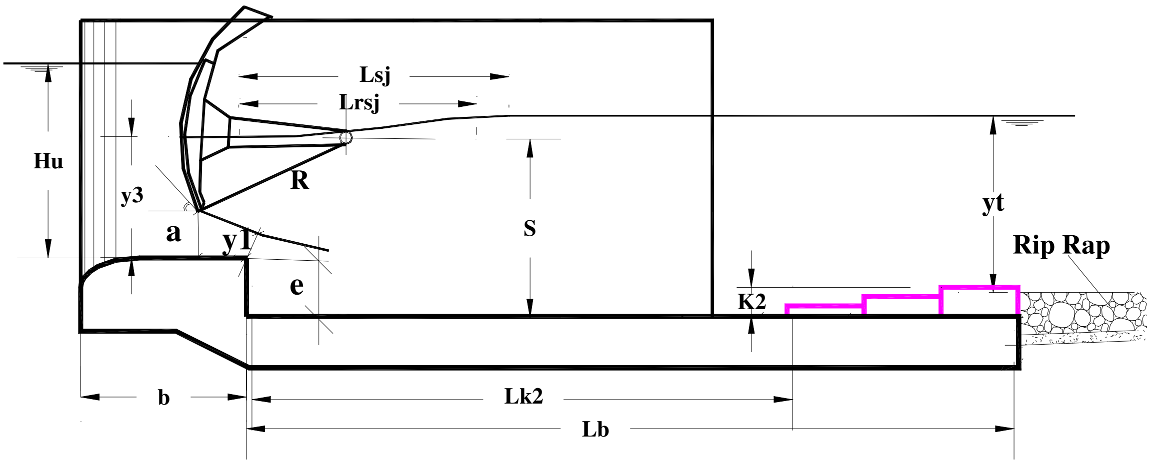


Figure 1. A definition sketch for the test physical model under submerged hydraulic jump conditions

EXPERIMENTAL SET-UP

The experiments were conducted using a 1.0 m wide, 26.0 m long and 1.20 m deep flume. The side walls along the entire length of the flume are made of glass with steel-frames, to allow visual inspection of the flow patterns and stability of bed protection. The horizontal bottom of the flume is made of concrete and provided with a steel pipe to drain the water from the flume. The tail water depth is controlled by a tailgate located at the downstream end of the flume. The water enters the flume from a constant head tank, which is fed by a centrifugal pump with a maximum discharge of 0.5 m^3/s (500 l/s) through an 16 inches pipeline. The flume is provided with another pump of capacity 150 l/s through a 10 inches pipeline to increase the discharge whenever required. A recirculating discharge system was used and there was underground reservoir of a total capacity of 80 m^3. The flume is provided with a mechanism at its input section to dissipate the energy at the inlet to suppress any excessive turbulence. Also, the flume is provided with an arrangement to ensure no leakage from the flume sides. The test model was fixed to the flume bed under the gate and extended from both sides DS and US of the gate.

Three models were tested. The basic model is shown in Figure 2 where e=0.09 m and k_2=0.09 m. Model two has e=0.17 m while model three has e=0.0m. The rigid bed is followed by a 3m long movable bed covered by rip rap with d_{50}=1.5cm. The upstream and the downstream parts of the radial gate are considered a part of the physical model, which was filled, with sand of 0.51 mm mean diameter. The upstream part was shaped in such way to enhance the flow and make it smooth when it approaches the gate. Also, the downstream part of the model was shaped to distribute the flow uniformly. The bed with movable particles, at the DS part of the model, comprises of three different layers, sand, filter, and rip rap with the same properties as in [3,4,5].

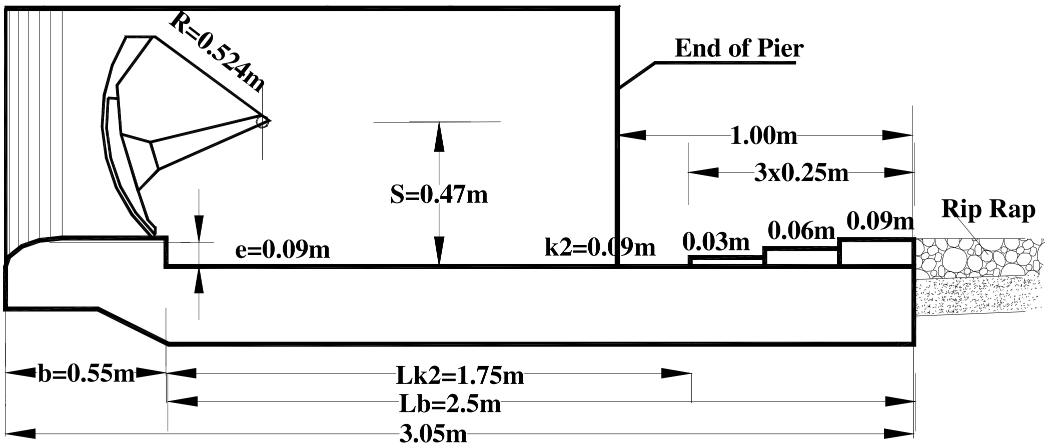


Figure 2. Definition sketch for one of the tested model

Equipments

An ultrasonic flowmeter was installed on the feeder pipe of 10 inches diameter and an electro-magnetic flowmeter was installed on the feeder pipe of 16 inches diameter. These two flowmeters were used for measuring the discharge during the tests with accuracy of ± 1%. A currentmeter for measuring the flow velocity was used. A data logger for collecting the data and transferred it to the computer was also used. Point gauges were used for measuring the scour hole and adjusting the water level at both upstream and downstream the gate A digital camera for recording the scour downstream the apron was employed. All equipments and instrumentations which need calibration were calibrated at HRI before and during carrying out the experimental work. The performance and accuracy of all equipments were checked weekly.

Limitations of Hydraulic Variables

The hydraulic variables were designed in such a way to cover a wide range of Barrages along the Nile River such as New Esna Barrage, New Naga Hammadi Barrages, Assuit Barrages, Delta Barrage, Zifta and Idfina Barrages. The main hydraulic variables were; the discharge, Q (ranges from 5 to 25 $m^3/s/m$), differential head, h (ranges from 3-8 m) and the downstream water depth, y_t (ranges from 6.5 to 12.5 m). These ranges of the hydraulic variables were based on the prototype hydraulic conditions of the different barrages on the Nile River. The hydraulic conditions for all test series were prepared based on the prototype hydraulic conditions. In the models the upstream head was kept constant, the discharge ranges from 40 to 190 lit/s, the downstream head varies from 0.47 to 0.64 m while the differential head varies from 0.16 to 0.33 m. For more details, one may consult Ali [3,4,5].

Undertaken Model Measurements

During each test, the flow velocity was measured at seven cross sections distributed along the centerline of the simulated bay. Also, the scour of the protected bed, downstream the apron, was measured. The submerged hydraulic jump characteristics were measured. The scour of the bed, downstream the apron and the jet under the radial gate, was recorded by the digital camera. The flow velocity were measured using an electromagnetic current-meter type EMS, manufactured by Delft Hydraulics, Holland. The current-meter was connected to a data logger, which receives the data directly from the currentmeter. The data logger also was connected to the computer, which receives the data from the data logger and save it in a file. The data logger was set to record 25 readings during time of 10 seconds at each point depth of the cross section. The currentmeter measured the flow velocity in two directions; in the flow direction, and perpendicular to the main flow.

The flow velocity was measured at seven cross sections with equal distances apart. The distance between each two cross section was equal to 0.50m. The first cross section was located at a relative distance of $X(=x/L_b=1/2.5)=0.4$ which is equivalent to 1.0m downstream the gate. Four cross sections were located on the apron area, and the other three sections were located on the rip rap area, downstream the apron. Figure 3 shows a typical measured velocity distribution at the seven selected stations for $h/H_u=0.33$, $e/H_u=0.0$, $k_2/H_u=0.14$ and $F_{r1}=1.46$. Also, five velocity values were shown on each profile; they are the near bed velocity 3 cm from the bed and the four velocities at 0.2, 0.4, 0.6, and 0.8 relative depth. Each velocity value is actually the average of 25 measurements in the main flow direction taken within 10 seconds.

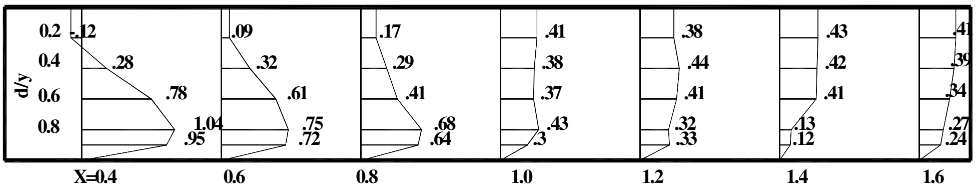


Figure 3. A typical dimensionless velocity distribution at the seven selected locations

Model Test Procedures

The following systematic steps [3,4,5] were followed to carry out any run of the total of 118 runs for the three tested models. Each model was tested under six flow conditions, and each flow conditions have six tailwater depths i.e., 36 conditions for each design. The following procedures were used to conduct these tests.

1. The level of the bed protection downstream the apron was adjusted at the same level as the apron.
2. The underground tank was filled with clear water.
3. The pump was operated and the flow was adjusted by the control valve and measured by an electromagnetic flowmeter or ultrasonic flowmeter.
4. The upstream and downstream water depths were adjusted to the required test condition.
5. After reaching the steadiness of flow, the following measurements were recorded: the gate opening (a), the back up water depth (y_3), the initial water depth of the jump (y_1), the length of jump (L_{sj}), the velocity profiles at seven cross sections and the velocity near bed at 3 cm from the bed level.
6. The bed protection downstream the apron was reshaped.
7. The tailwater depth was changed and steps no. 5 and 6 were repeated for six tailwater depth condition.
8. The discharge was changed and steps 5, 6, 7 and 8 were repeated.
9. The test procedure was repeated for each of the three tested models.

ANALYSIS OF RESULTS AND DISCUSSIONS

The collected experimental data were processed and presented in dimensionless forms in the light of equations (1) and (2). Since the upstream head was kept unchanged while the downstream depth was changing, the resulting values of h/H_u were 0.49, 0.44, 0.33, 0.29 and 0.24. Also, k_2 is kept constant to 0.09m, and hence the value of k_2/H_u is equal to 0.14. On the other hand, the pool inlet height, e is changing from 0.0 to 0.17, the e/H_u have three values of 0.27, 0.14 and 0.0. Since the outlet conditions k_2/H_u is kept constant, the following discussion will concentrate on the effects of h/H_u and the inlet conditions of the pool (e/H_u) on the velocity distribution, velocity decay, length of submerged jump, energy dissipation due to the jump and the scour DS the pool-type stilling basin.

Velocity Distribution and Velocity Decay

Figure 4 shows a typical variation of velocity distribution profiles for $h/H_u=0.24$, $e/H_u=0.27$ and $k_2/H_u=0.14$ for F_{r1} equals (a) 2.08, (b) 1.51 and (c) 1.33. Also, Figure 5 presents another typical variation of velocity distribution profiles for $h/H_u=0.44$, $k_2/H_u=0.14$ and $F_{r1}=2.6$ for $e/H_u=$ (a) 0.27 (b) 0.14 and (c) 0.0. Analysis of these figures and all plotted measured velocity profiles under submerged hydraulic jump conditions indicated two parts: main forward flow (lower part) and the reversed flow (upper part). Also, the dimensionless longitudinal velocity distribution reaches its typical velocity profile (fully developed flow) at particular relative horizontal distance “X” depending upon the values of h/H_u, e/H_u and F_{r1}. Moreover, for a certain value of h/H_u, e/H_u and “X” the forward flow was increased as Froude number “F_{r1}” decreased and the reason for that was due to increasing the gate opening and consequently increasing the thickness of the forward flow. Also, it was observed that by decreasing the h/H_u for a certain value of e/H_u the thickness of the forward flow increases and travels for long distance with a high velocity and the backward flow ends at a relative distance “X” equals 1.0 and in some cases it ends at $X<1.0$. Previous investigations by the authors [16] indicated that the backward flow ends at $X>1.0$ when no end step (single or multi) is present. This proves an advantage of the end multi-step.

Comparing between velocity profiles for different e/H_u at the same $F_{r1}=2.6$ and fixed relative outlet-height of the pool $k_2/H=0.14$ (Figure 5) and constant h/H_u indicates that the forward flow and the backward flow were increased by increasing the relative vertical distance e/H_u. Moreover, the dimensionless velocity profile reaches its typical profile in a short distance from the gate by decreasing the relative inlet-height of the pool e/H_u for a certain values of h/H_u and F_{r1}. Similar findings were observed for other values of h/H_u.

On the other hand, the dimensionless near-bed velocity decay, v_b/v_1, was plotted for all investigated cases for all values of h/H_u, e/H_u and F_{r1} at $k_2/H_u=0.14$. Typical plots are presented in Figure 6 for different values of Froude numbers at $h/H_u=0.33$, $e/H_u=0.14$, $k_2/H_u=0.14$ and in Figure 7 for $h/H_u=0.44$ Fr1=2.55, $k_2/H_u=0.14$ and different e/H_u of 0.27, 0.14 and 0.0. It is observed that the values of the velocities near bed along the stilling basin were increased as Froude number F_{r1} was decreased. Moreover, it was noticed that the velocity near bed reached the end of apron with low values as e/H_u was decreased for fixed value of h/H_u. Specifically, v_b/v_1 is the lowest for $e/H_u=0.14$. This indicates an advantage of constructing a pool of the height at both the inlet and the outlet of the pool ($e/H_u=k_2/H_u=0.14$). Comparing the results with the previous ones for $e/H_u=0.0$ (flat bed) revealed that the present yields better results for the velocity near bed and reaches the end of apron with lower velocity. Generally, the velocity near bed at the end of apron was reduced by about 30% to 50% compared to no step conditions.

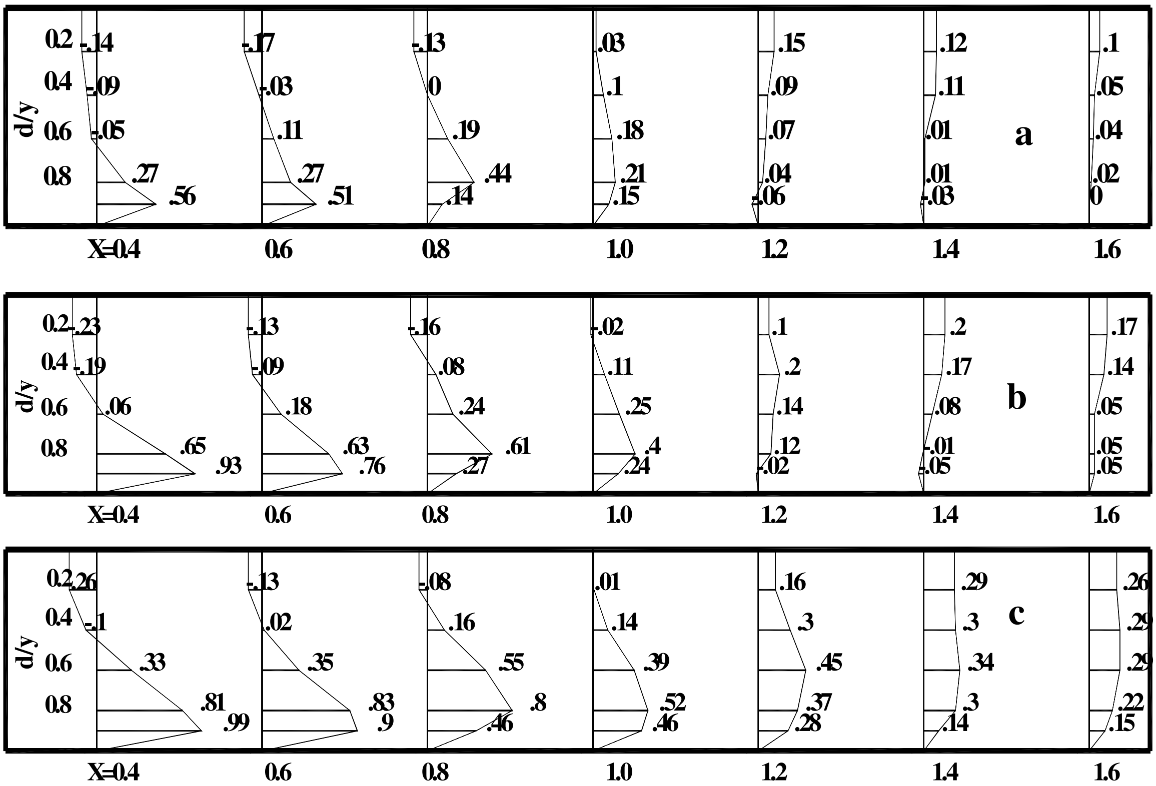


Figure 4. Variation of velocity distribution profiles for h/H_u=0.24, e/H_u=0.27 and k_2/H_u=0.14 for F_{r1} equals (a) 2.08, (b) 1.51 and (c) 1.33

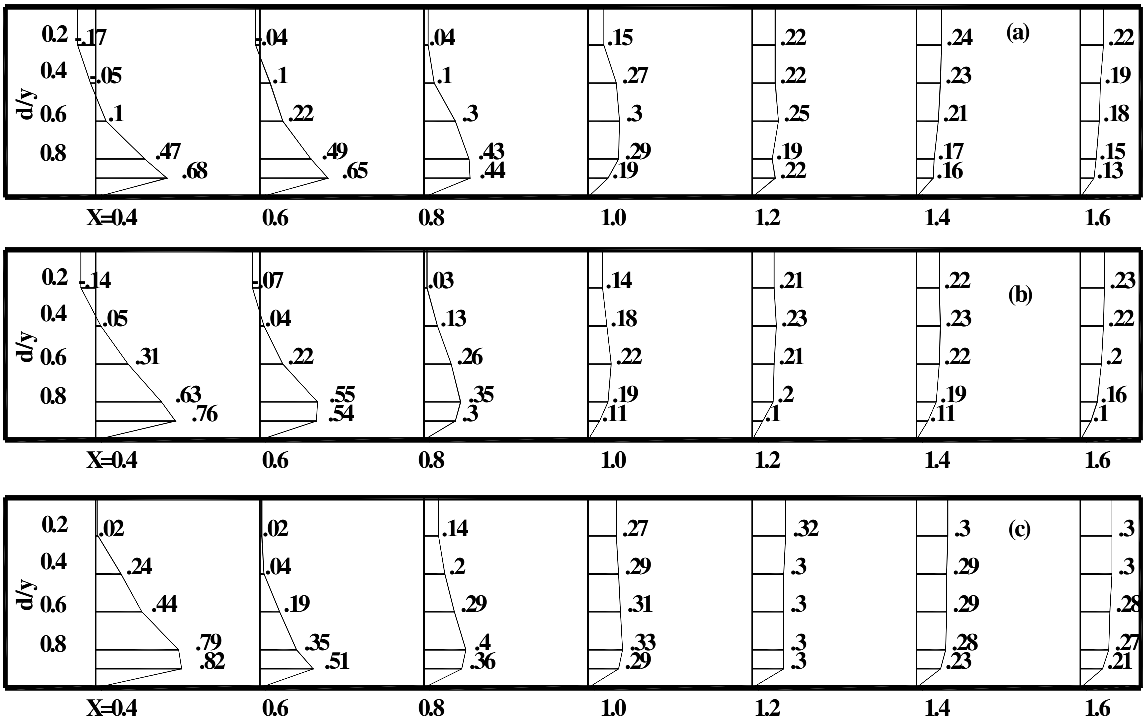


Figure 5 Variation of velocity distribution profiles for h/H_u=0.44, k_2/H_u=0.14 and F_{r1}=2.6 for e/H_u= (a) 0.27 (b) 0.14 and (c) 0.0

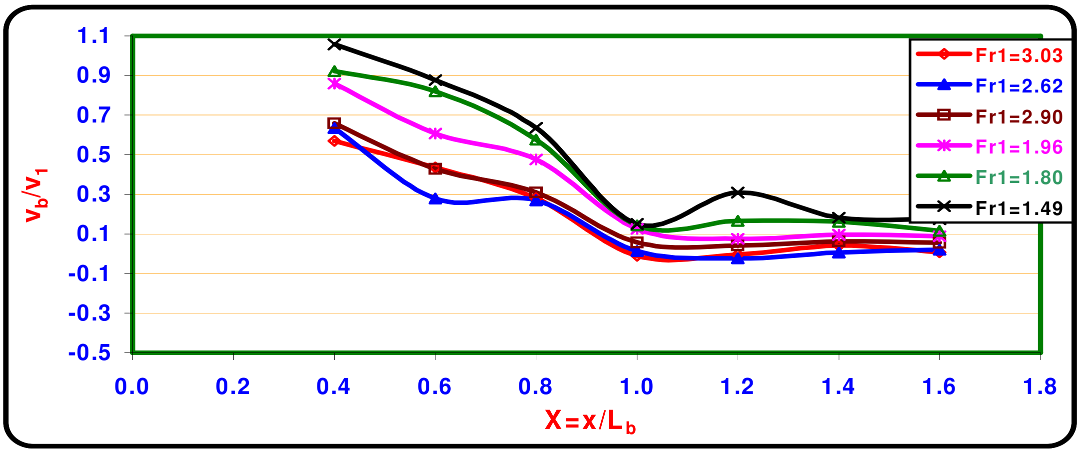


Figure 6. Relationship between v_b/v_1 and X at $h/H_u=0.33$, $e/H_u=0.14$, $k_2/H_u=0.14$ and different F_{r1}

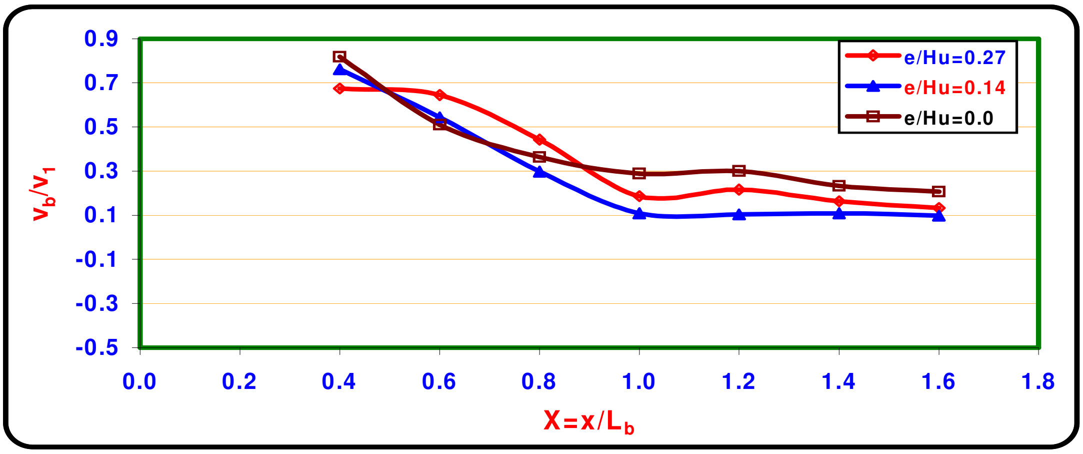


Figure 7. relationship between v_b/v_1 and X for $h/H_u=0.44$ $F_{r1}=2.55$, $k_2/H_u=0.14$ and different e/H_u of 0.27, 0.14 and 0.0

Energy Dissipation and Length of Submerged Hydraulic Jump

Figure 8 presents the relationship between L_{sj}/y_1 and F_{r1} for $k_2/H_u=0.14$, $e/H_u=0.14$ and different h/H_u of 0.44, 0.33 and 0.24 while Figure 9 presents the same for $k_2/H_u=0.14$, $h/H_u=0.33$ and different e/H_u of 0.27, 0.14 and 0.0 as typical plots. These figures and others (not presented here to reserve space) indicated that the shortest length of the submerged hydraulic jump was obtained when $e/H_u=0.0$ for all values of h/H_u and all values of F_{r1}. This means that the zero-inlet height of the pool is better than any other height regarding these two parameters. Keeping e/H_u constant, the L_{sj}/y_1 increases be decreasing h/H_u which reflects the impact of the increasing weight of water along the jump length. Also, analysis of the dimensionless energy loss for all cases indicated that the case with $e/H_u=0.0$ produces the largest values of the maximum energy dissipation compared to all other cases regardless of the value of h/H_u. Typical plots to support these findings are presented in Figures 10 and 11. The first figure is for $k_2/H_u=0.14$, $e/H_u=0.14$ and different h/Hu of 0.44, 0.33 and 0.24 while second is for $k_2/H_u=0.14$, $h/H_u=0.33$ and different e/Hu of 0.27, 0.14 and 0.0. Previous investigations by Alhamed et al [6,7,8] and Negm et al [20,21] concluded that the presence of the sill under the gate increases (pool of zero outlet height) the length of the hydraulic jump compared to no sill case in both cases of free and submerged flow conditions. Other investigation [5,16] indicated that the length of the jump was reduced when an end step is constructed DS gates without sill (pool of zero inlet height). The net result is a reduction in the length of the jump and an increase in the energy dissipation due to the combined effect of $e/H_u=0.0$ and $k_2/H_u=0.14$. These results corporate well with those obtained by the authors [4] in a previous investigation for basins without end step.

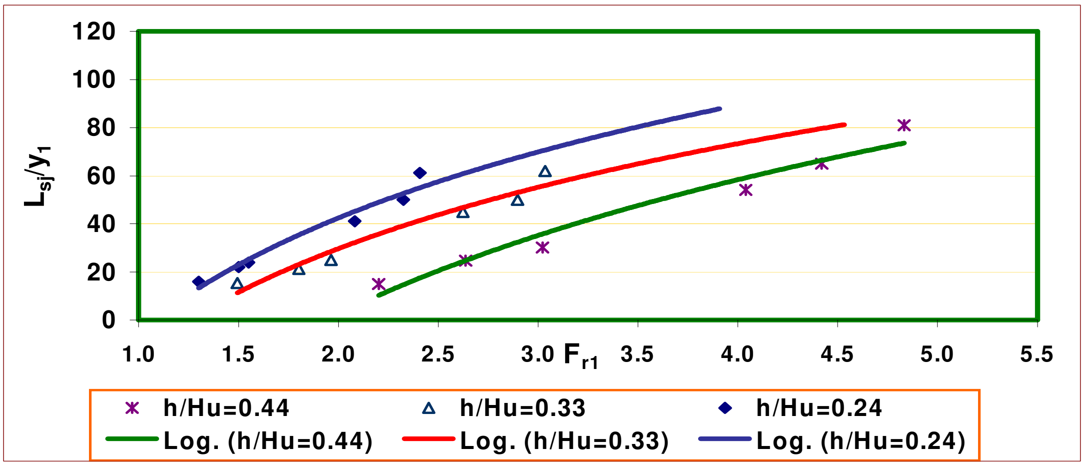


Figure 8. Relationship between L_{sj}/y_1 and F_{r1} for $k2/H_u=0.14$, $e/H_u=0.14$ and different h/H_u

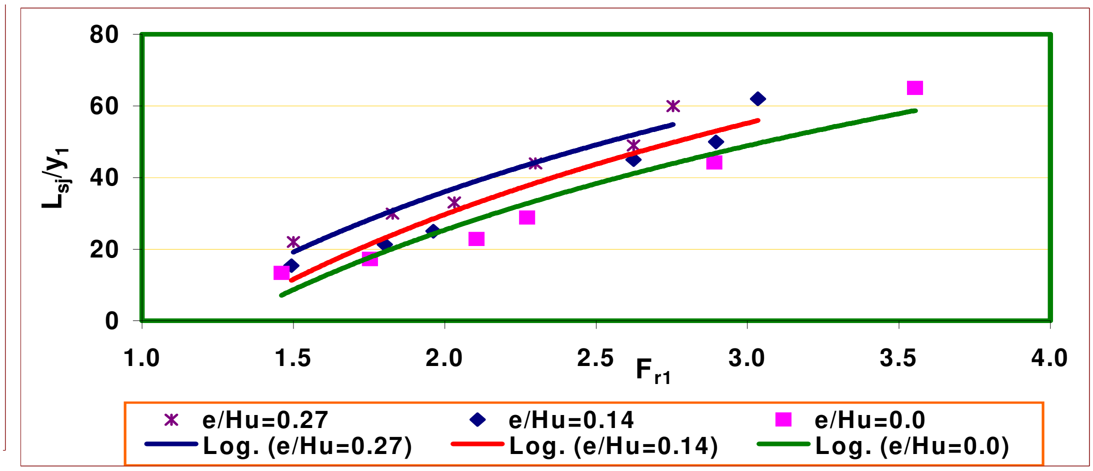


Figure 9. Relationship between L_{sj}/y_1 and F_{r1} for $k_2/H_u=0.14$, $h/H_u=0.33$ and different e/H_u

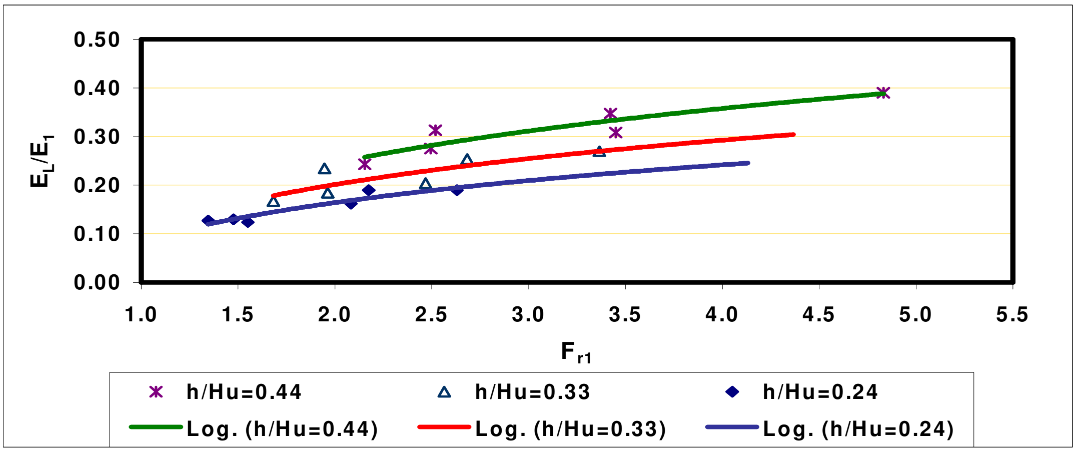


Figure 10. Relationship between E_L/E_1 and F_{r1} for $k_2/H_u=0.14$, $e/H_u=0.14$ and different h/H_u

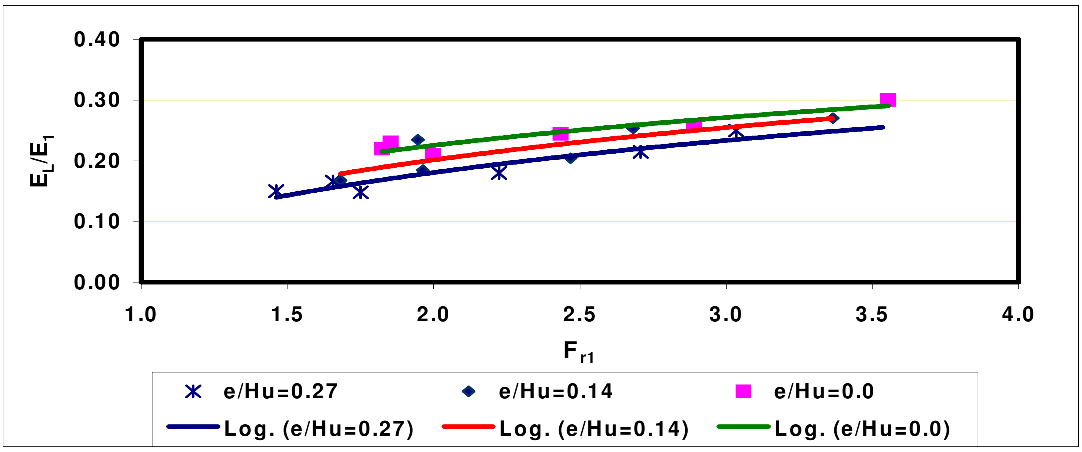


Figure 11. Relationship between E_L/E_1 and F_{r1} for $k_2/H_u=0.14$, $h/H_u=0.33$ and different e/H_u

Scour Downstream of Stilling Basin

Analysis of all measured scour profiles indicated that the value of the maximum scour depth and length to the maximum scour depth (scour length) were increased by decreasing Froude number F_{r1} for each value of "h/H_u", Figure 12. These results are well explained by observing the velocity profiles and the velocity decay along the stilling basin and over the protected area downstream the apron. Further analysis of all plotted profiles, revealed that the relative values of the scour depth and scour length were decreased in case of design relative height on pool inlet of e/H_u, Figure 13. Also, the scour depth and length were increased when $e/H_u=0.0$ whereas, the height of the water depth over the bed protection was small and the velocity near the bed was high enough to cause scour.

In addition, it was observed that the minimum scour depth and length was obtained with when $e/H_u = 0.14$. On the other hand, it was found that the maximum scour depth was obtained when $e/H_u = 0.0$ especially with "h/H_u" equal 0.44 and 0.33.

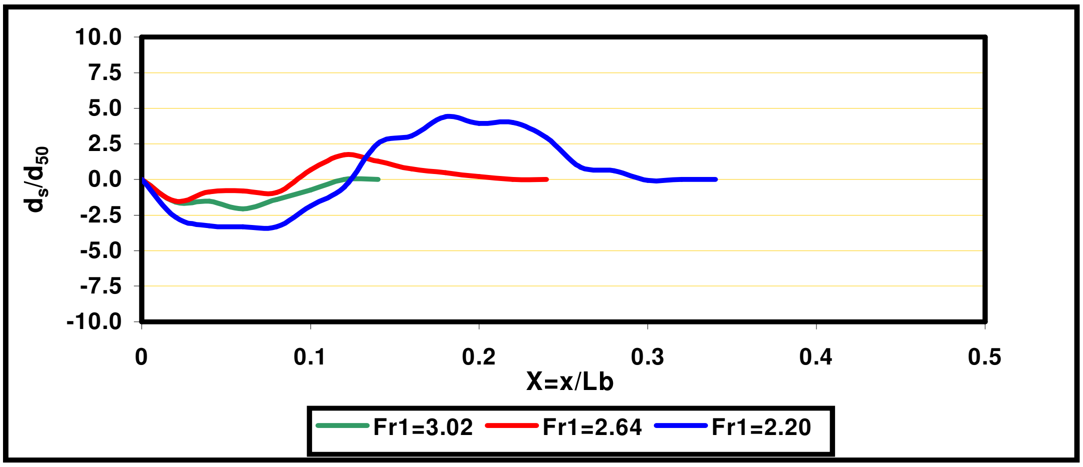
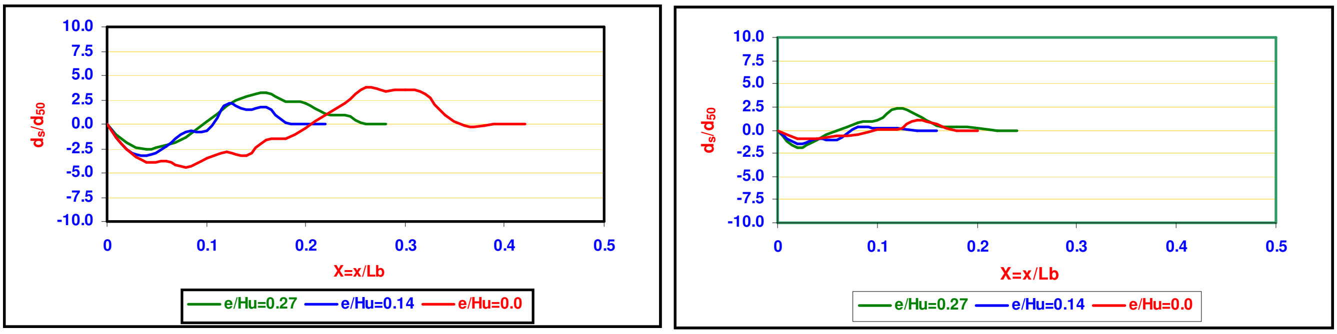


Figure 12 Variation of dimensionless scour profile d_s/d_{50} for e/H_u=0.14 at k_2/H_u=0.14 and h/H_u=0.44 for different F_{r1}



(a) (b)

Figure 13 Variation of dimensionless scour profile d_s/d_{50} for e/H_u=0.27, 0.14 and 0.0 at k_2/H_u=0.14 and h/H_u=0.33 for F_{r1} (a) = 1.60 and (b) = 1.80

CONCLUSIONS

Within the experimental set-up and limitations, the analysis and discussions presented above highlighted the following conclusions:

1- The velocity near the bed was reduced significantly (about 30 to 50%) when both the inlet-height equals the outlet height of the pool of the stilling basins, i.e. when $k_2/H_u=e/H_u=0.14$.

2- The length of the submerged hydraulic jump is minimized and the energy dissipation was maximized when both the inlet-height equals the outlet height of the pool of the stilling basins, i.e. when $k_2/H_u=e/H_u=0.14$.

3- The minimum values of the maximum scour depth were observed when the pool of the stilling basin had heights at both the inlet and outlet conditions, i.e., $k_2/H_u=e/H_u=0.14$.

4- The obtained results in the present paper confirmed the previously published results by the researchers and other investigators.

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NOMENCLATURE

d_{50}	The median particle size of the bed material	-
e	Height of drop at the beginning of the pool	L
e/H_u	Relative height of the pool inlet	-
E_1	The specific energy at the beginning of the jump	L
E_2	The specific energy at the end of the control volume	L
E_L	The energy dissipated in the jump (E_1-E_2)	L
F_{r1}	Froude number at vena contracta ($v_1/(gy_1)^{0.5}$)	-
h	The head difference, (upstream head – downstream head)	L
h/H_u	The relative differential head	-
k_2	maximum height of end multi-step	L
k_2/H_u	relative height of end step (end step of multi-steps)	-
L_b	The basin length	L
L_{sj}	Length of submerged hydraulic jump	L
Q	The flow rate	L^3T^{-1}
d_s	The maximum scour depth	L
v	Velocity at any point depth of the profile	m/s
v_1	The average flow velocity at vena contracta	LT^{-1}
v_2	The average flow velocity at the end of jump	LT^{-1}
	which the velocity is one-half the maximum velocity	L
v_b	Velocity near bed	m/s
y_1	The initial water depth of the classical jump	L
y_t	The tailwater depth at the end of the basin	-
x	The distance from the radial gate	L
X	The relative horizontal distance from the gate ($=x/L_b$)	-