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Numerical Study for Negative Step Stilling Basin

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ABSTRACT

The hydraulic jump is a natural phenomenon that occurs when the flow transitions from a supercritical flow to a subcritical flow within a short distance. The hydraulic jump is considered one of the most effective methods of dissipating energy through the stilling basin downstream of the control structures. The energy dissipation in the stilling basin contributes to protecting the area downstream of the control structures from erosion which may cause the collapse of the structure. The aim of this study is to calibrate the Flow 3D program using practical experiments. A three-dimensional numerical simulation was performed using the Flow 3D program to investigate the dissipation of energy due to a hydraulic jump through stilling basins with a negative step and compare the results of the study with the results of the practical experiments. (*The simulated experiments in this paper using the Flow 3D program were performed at the National Centre for Water Research, Egypt.*) It was clear from the comparison that the program has a high ability to simulate the phenomenon and to show results that are close to reality with an error of not more than 10%.

1. Introduction

The hydraulic jump is considered one of the most effective methods of dissipating energy in heading-up structures because it dissipates a large amount of the total energy.

For heading-up structures, the energy is needed to be dissipated to overcome the problems of water effects on the river waterway or the structure basin downstream the spillway.

Energy dissipation helps to reduce erosion occurring in the spillway stilling basin downstream of the structure, which affects the stability of the structure.

A stilling basin is designed to dissipate the kinetic energy of the flow in a hydraulic jump. There are several ways to increase the dissipation of energy and reduce erosion, whether by changing the stilling basin shape, placing obstructions in the stilling basin, or sometimes introducing an abrupt drop or rise in bed level to minimize the tailwater effects and stabilize the jump location.

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Several numbers of researchers in the field of hydraulics have studied these types of basins.

Below are some researchers and their research that have been done on the effect of a sudden drop in the bed level of a stilling basin on the hydraulic jump.

Rouse [1] deduced two theoretical equations for A-type and B- type jump at the abrupt vertical drop; By assuming traditional approach flow as;

For A- type jump:

$$F_1^2 = \frac{Y[\,(Y-S\,)^2-1\,]}{2(Y-1)} \qquad (1)$$

For B- type jump:

$$F_1^2 = \frac{Y[\,Y^2-(1+S\,)^2]}{2(Y-1)} \qquad (2)$$

Where:

F_1 = initial Froude number, $F_1^2 = q^2/(gh_1^3)$,
q = discharge per unit width, h_1 = initial flow depth for hydraulic jump, h_2 = sequent flow depth for hydraulic jump, $Y = h_2/h_1$ = sequent depth ratio,
s = step height, $S = s/h_1$ = relative step height

Hager and Bretz [2] found no significant difference between the 45° sloping and the vertical step geometry.

Three types of jumps for negative step were considered, Figure 1.

1) The A-jump, where the extreme positions of jumps at a negative step for which the end of roller is at the step section, and
2) The minimum B- jump, for which the toe is downstream from the step where the supercritical flow has again become parallel to the bottom
3) The B- jump, for which the toe of jump is at the step section, still decreasing the tailwater, the jump moves downstream, finally yields the minimum B-jump, as previously described.

If the tailwater is either higher than needed for the A jump, or lower than needed for the minimum B-jump to form, the jump moves away from the step either in the up- or in the downstream direction, respectively.

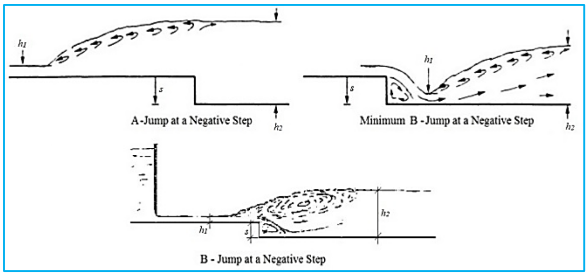

Fig. 1. A-jump, B-jump, and minimum B-jump at negative step (Hager and Bretz [2])

Hager and Bretz [2] presented a detailed comparative experimental investigation on jumps at negative steps along with positive steps, and analytical equations were introduced for comparing these results with the formed jumps at negative step in a horizontal rectangular channel, which have good agreement with experimental data as follows:

For A-type jump with a negative step, Hager and Bretz [2] deduced the same equation (1) for Rouse [1].

For B-type jump with a negative step:

$$F_1^2 = \frac{Y[Y^2 - S^2 - 1\,]}{2(Y-1)} \qquad (3)$$

Quraishi and Al-Brahim [3] produced a mathematical model of hydraulic jump in a rectangular sloping channel provided with a positive or negative step; they also derived equations for A-type jump and B-type jump on a sloping floor provided with a step, and they concluded that:

1) The jumps on negative steps are more stable.
2) The jumps on positive steps are more compact.
3) The efficiency of B-type jumps was found to be higher than that of A-type jumps.

The efficiency of a negative B-type jump had the same order of magnitude as that of a classical jump in a horizontal channel.

Negm [4] developed theoretical equations for computing the pressure force on the face of a positive or negative step in a horizontal stilling basin. The equations were based on the application of one-dimension momentum and continuity equations, and his results indicated that:

1) The pressure distribution on the face of the step was smaller than the hydrostatic one when the conditions of the hydraulic jump were prevailed.

2) Conditions of a negative B-type jump gave values of the pressure distribution coefficient lesser than those of a negative A-type jump.
3) Cavitations were most likely to occur near the face of the negative step, especially for the negative B-type jump.

El-Saiad [5] studied the effect of different baffle block heights and positions downstream of drop structures. It was found that:

- The relative depth of the jump increases with the increase in relative drop height.
- The relative energy loss decreases with the increase in relative drop height.
- The relative jump length increases with increasing the relative drop height.

Hazzab and Bakhti [6] conducted a comparative analysis of the positive and negative steps in a forced hydraulic jump; the beginning of his work related to the experimental analysis of stability.

He concluded that a stilling basin is more effective with a negative step than with a positive step to stabilize the jump. The study of effectiveness allowed classifying the various types of jumps through the two steps according to their efficiency. It was shown that the maximum efficiency is for the B-jump type negative step, followed by the B-jump type positive step, then the A-jump type negative step, and finally the A-jump type positive step with the minimum efficiency.

The end of the work was devoted to the study of the compactness of the jump with a positive step and a negative step. It made it possible to show in experiments, through the comparison of the relative lengths of the various types of jumps, that the jumps with negative steps were the least long and thus the most compact compared to those with positive steps.

Fathi et al. [7] studied the characteristics of forced hydraulic jumps in stilling basins for enforced cases due to tail water level or dam site arrangement and construction. The case with a single tall sill was simulated in a horizontal flume downstream of a sluice gate. The results of the experiments were compared with the classical hydraulic jump, and the significant effect of tall sills on the dissipation of energy over shorter distances was confirmed. Furthermore, the generated jumps were classified based on the ratio of sill height to basin length.

The results of the experiments have proved the considerable effect of sill height and position on the sequent depth ratio and the shortening of the basin length, thus reducing costs. In contrast with ordinary sills, they are able to raise water level upstream of the sill and dissipate a considerable amount of flow energy through the sudden interexchange of kinetic and potential energies.

El-Tohamy [8] used the Flow 3D program in a simulation of an experimental study to improve the performance of gabion spillways under different flow conditions in order to check the accuracy of the program. The Flow 3D program gave results with ±5% error in upstream depth and ±10% error in initial depth; these ratios indicate acceptable accuracy to use this program in simulation.

El-Bagoury [9] used the Flow 3D program in a simulation of an experimental study to predict the depth of erosion around the foundations of the high-voltage electricity towers located inside the flood valleys in addition to reducing the dimensions of that erosion. To verify the accuracy of the program, a comparison was made between a numerical model using the Flow 3D program and previous experimental results by Mossa [10]. The error rate in the results of that numerical model was about ± 8.0%, which indicates acceptable accuracy to use this program in simulation.

Dermawan et al. [11] conducted an experimented study on a hydraulic model of the horizontal and USBR II stilling basin to investigate flow behavior and energy dissipation under different flow conditions. The hydraulic model was carried out by making a series of bottom lowering of horizontal and USBR II stilling basin.

The results of the experiments showed that the depth of flow in the USBR II stilling basin experienced an increase in the water level at the toe of the chute way for all flow discharges. In USBR II, equipped with baffle blocks at the toe and end point of the stilling basin, the flow becomes more turbulent than in the flat stilling basin that is not equipped with baffle blocks. The depth of flow after the hydraulic jump was also higher in USBR II than in the flat stilling basin. It was found that, on higher discharge with a higher difference in overflow height, the performance of the USBR II in dissipating energy is better than that of a flat stilling basin.

Rafael et al. [12] presented the results of a combination of experimental and numerical research on the performance of stilling basins of spillways with highly convergent chutes.

The comparison between the energy dissipation of the stilling basins with flat slabs and baffle blocks shows that the latest are more efficient. Because of that, the cost savings of using such blocks can be significant. The results obtained could be applied in different cases, such as increasing the capacity of existing spillways and protecting dams against overtopping.

The application of highly convergent chute spillways in new dams could lead to a reduction in the cost of the stilling basin compared to conventional hydraulic jump energy dissipators.

2. Flow 3D numerical model where its governing equations [13]:

The Flow-3D program provides a complete and versatile CFD “Computational Fluid Dynamics” simulation platform for engineers investigating the dynamic behavior of liquids and gases in a wide range of industrial applications and physical processes.

The simulation program (Flow 3D) was used in simulating the phenomenon (hydraulic jump over a negative step), and this program passes through a set of stages as follows:

Firstly, to create a mesh, Flow-3D uses an approach that combines the advantages of a simple rectangular grid with the flexibility of a deformed mesh. Such an approach is called a "free formation grid" because the geometry can be freely changed independently.

This mechanism eliminates the hard task of generating a finite element mesh.

Flow-3D uses a fixed grid of orthogonal elements that facilitates the generation and provides many desirable properties (e.g., regularity improves accuracy, reduces memory requirements, facilitates numerical approximation).

Secondly, Flow-3D includes a special technique known as the FAVOR (Fractional Area Volume Obstacle Representation) method, which is used to describe the geometry on a rectangular grid of any form, The FAVOR philosophy is that the numerical algorithms in the finite volume method are based on information including only one value of pressure, speed, and temperature for each element; thus, the FAVOR method retains the simplicity of rectangular elements in the presentation of complex geometries in a compatible manner with the use of the averaged flow characteristics for each volume element.

The third important feature of Flow-3D is its method of processing the surface of the flowing fluid. This program uses special numerical methods for tracking the position of surfaces, and for the proper application of the boundary conditions on them, the free surfaces are modelled using the finite volume method.

Some of the other Computational Fluid Dynamics (CFD) programs claim Volume of Fluid (VOF) implementing the method, although in reality they use only one or two of the three fundamental ingredients constituting the VOF method.

Potential users of CFD software should be aware that these pseudo-VOF schemes will often give incorrect results; Flow-3D includes all of these ingredients suggested for successful processing of the free surface.

Moreover, Flow-3D includes significant improvements to the starting VOF method for increasing the accuracy of boundary conditions and tracking interfaces; this implementation method is called "TruVOF".

Flow-3D is widely used around the world in both commercial and scientific projects to solve the most complex problems in various areas. Flow-3D can solve problems in the aerospace industry, shipbuilding, coating, and hydraulic engineering.

3. Work sequence for Flow 3D program verification:

The purpose of this study is to verify the ability of the Flow 3D program to simulate the hydraulic jump over a sudden drop (negative step) in the stilling basin downstream of the control structures, and to achieve that, the practical results from Hager and Bretz [2] research were used in order to check this program. The research involved studying the rise and drop (sudden and gradual) at the bottom of the channel in practice on a model of a rectangular horizontal channel with the following dimensions:

Bed width B = 0.50m, negative steps of height s = 0.051m and s = 0.076m, angle of step inclination $\alpha = 45°$ and $\alpha = 90°$, as shown in Figure 2, the horizontal channel length is 10m, and its upstream end is bounded by a standard spillway of height 0.70m. The discharge values ranged from 20 to 200 lit/sec.

Hagar's set of experiments for (A-Jump, Negative Step) contains three experiments. For each of these experiments, the discharge value (Q) is passed, the value of h2 is set, as shown in Table 1, and the corresponding value of h1 is obtained, as shown in Table 2.

Table 1. Hagar's set of experiments for (A-Jump, Negative Step) "values of Q and h2 input"

Experiment No. 1 s = 5.1cm α = 45°					
Q lit/sec	40	60	80	100	120
h_2 … cm	25.2	31.3	36.2	40.3	43.7
Q lit/sec	140	160	180	200	
h_2 … cm	47.0	50.5	54.1	56.4	
Experiment No. 2 s = 7.6 Cm α = 45°					
Q lit/sec	20	30	50	75	100
h_2 … cm	18.7	22.5	30.7	37.0	42.4
Q lit/sec	125	150			
h_2 … cm	46.3	50.1			
Experiment No. 3 s = 7.6 Cm α = 90°					
Q lit/sec	20	30	50	75	100
h_2 … cm	-	22.6	30.4	37.4	42.6
Q lit/sec	125	150			
h_2 … cm	47.0	51.5			

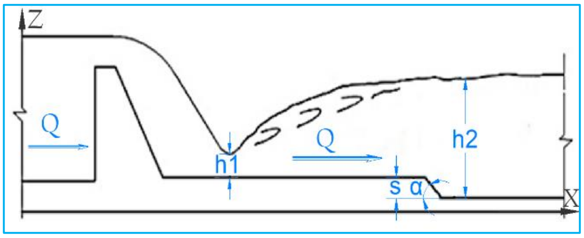

Fig. 2. Model of rectangular horizontal channel used in Hager’s experiments (Hager and Bretz [2])

The most important results for Hager’s experiments (A-Jump, Negative Step) are shown in Table 2.

Thus, all these three experiments were simulated using the Flow 3D program, and the relationship between each value from 22 values for (h1) resulting from Hagar's experiments and the corresponding value from 22 values for (h1) resulting from the Flow 3D program was drawn in one chart, Figure 3.

Also, the relationship between F1 and the sequent depth ratio Y = h2 / h1 for each of Hagar's experiments and the Flow 3D program was drawn in the chart, Figure 5.

In addition, the relationship between F1 and relative wave height $(Y+S)_{max}$ for each of Hagar's experiments and the Flow 3D program was drawn in the chart, Figure 6.

Table 2. Results of Hager’s experiments (A-Jump, Negative Step)

Q lit/sec	40	60	80	100	120	s = 5.1cm α = 45°
h_1 … cm	2.5	3.55	4.4	5.5	6.5	
$h_{max}+s$	33.4	39.5	47.0	no wave		
Q lit/sec	140	160	180	200		
h_1 … cm	7.5	8.6	9.6	10.6		
$h_{max}+s$	no wave					
Q lit/sec	20	30	50	75	100	s = 7.6 Cm α = 45°
h_1 … cm	1.85	2.3	3.15	4.55	5.9	
$h_{max}+s$	19	25.5	34.6	43.2	48.6	
Q lit/sec	125	150	175	200		
h_1 … cm	7.1	8.4				
$h_{max}+s$	-	-	-	-		
Q lit/sec	20	30	50	75	100	s = 7.6 Cm α = 90°
h_1 … cm	1.85	2.3	3.15	4.55	5.9	
$h_{max}+s$	-	24.7	35.2	44.1	48.2	
Q lit/sec	125	150	175	200		
h_1 … cm	7.1	8.4				
$h_{max}+s$	47.7	-				

When substituting for the values of each of (h_1, h_2, and S) resulting from Hagar's experiments in equation No. (1), the values of (F1 th.) according to the equation were obtained, as the relationship between (F1 th.) and (F1 ex.) resulting directly from Hagar's experiments was drawn (Figure 7).

Similarly, in the same figure, a relationship was drawn between (F1 th.) and (F1 ex.) resulting from the Flow 3D program.

4. Analysis of Data:

All of Hager's experiments for A-Jump, negative step, were simulated using the Flow 3D program.

Figure 3 shows the relation between (h1) for the Flow 3D model and (h1) for Hager's experiments (A-Jump, negative step), while Figure 4 shows the relation between (1.10*h1) for the Flow 3D model and (h1) for Hager's experiments (A-Jump, negative step).

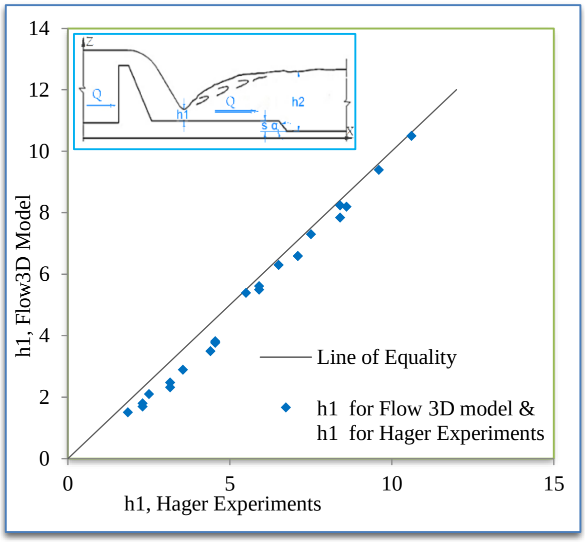

Fig. 3. Relation between (h1) for Hager experiments and (h1) for Flow 3D model

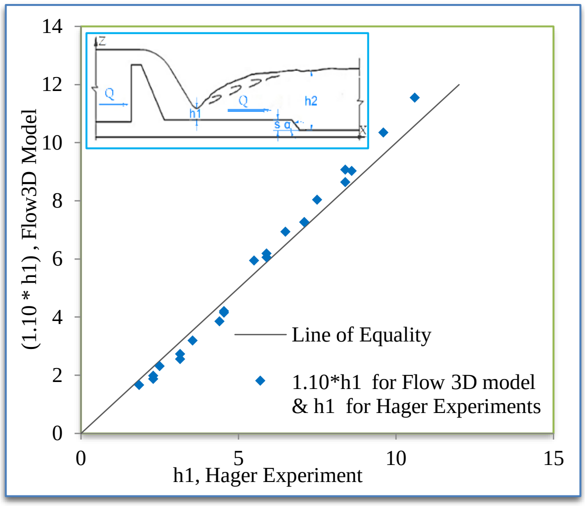

Fig.4. Relation between (h1) for Hager experiments and (1.10*h1) for Flow 3D model

It appears from these two charts that the results of the Flow 3D program were largely similar to the results of Hagar's practical experiments for A-Jump, negative step, with an average error of (-10%).

Figure 5 shows the relationship between F1 and the sequent depth ratio Y = h2 / h1 for each of Hagar's experiments and the Flow 3D program. It is clear from the figure the similarity of that relationship for each case of the three Hagar's experiments and the corresponding case for the Flow 3D program.

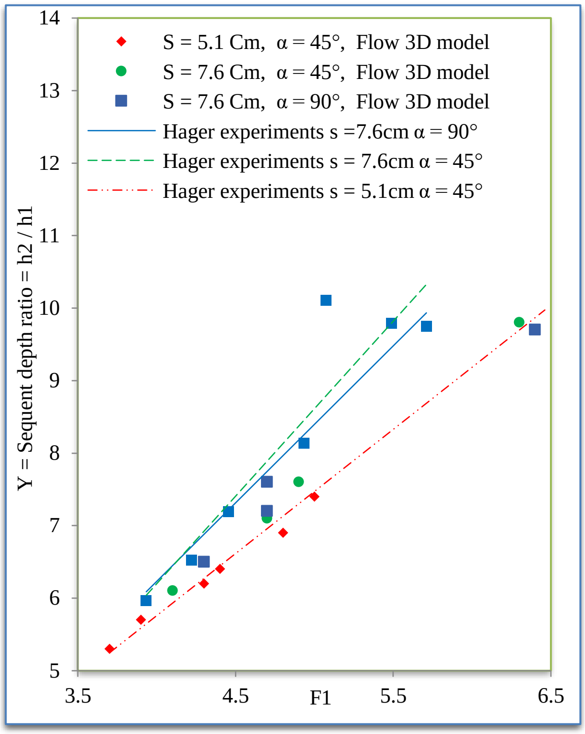

Fig. 5.

(Lines): Relation between sequent depth ratio (h2/h1) and (F1) for Hager experiments.
(Points): The same relation for Flow 3D model, for A-Jump, negative step s =7.6cm α = 90°, s = 7.6cm α = 45°, and s = 5.1cm α = 45°

Figure 6 shows that the relationship between F1 and relative wave height (Y+S)max for the Flow 3D program is very similar to the same relationship for Hagar's experiments.

Figure 7 shows that the values of (F1 ex.) for Hagar's experiments are very close to the values of (F1 th.) that result from substituting for the values of each of (h_1, h_2, and S) resulting from Hagar's experiments in equation No. (1). Also, Figure 7 shows that the values of (F1 th.) are very close to the values of (F1 ex.) resulting from the Flow 3D program.

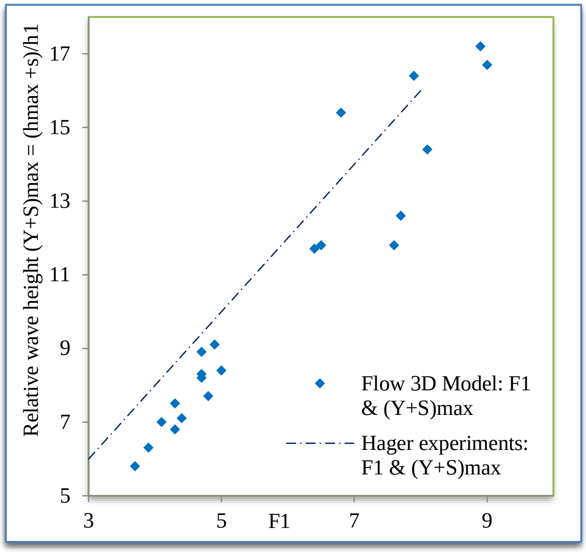

Fig. 6.
(Line): Relation between relative wave height (Y+S) max and (F1) for Hager experiment.
(Points): The same relation for Flow 3D model, for A-Jump, negative step s =7.6cm, α = 90°, s = 7.6cm α = 45°, and s = 5.1cm α = 45°

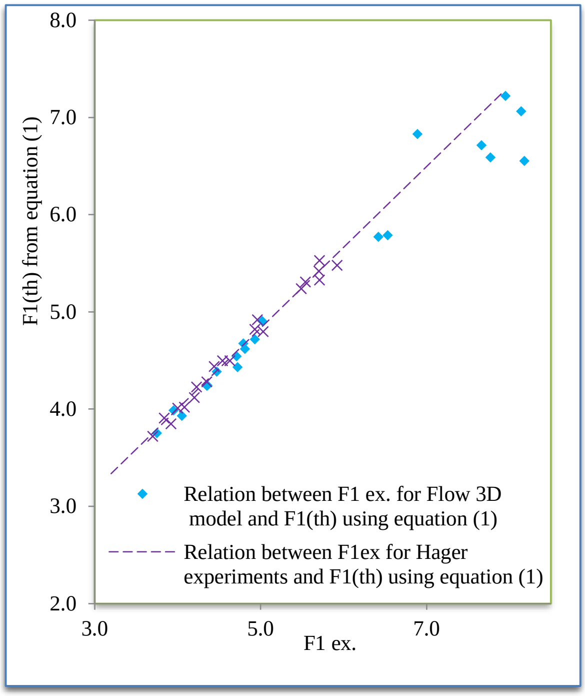

Fig. 7.
(Line): Relation between F1ex. for Hager experiments and F1(th.) using equation (1)
(Points): Relation between F1ex. for Flow 3D model and F1(th.) using equation (1) for A-Jump, negative step s = 7.6cm α = 90°, s = 7.6cm α = 45°, and s = 5.1cm α = 45°

5. Conclusions

Based on the detailed observations of Hagar's practical experiments for A- Jump, negative step, which were simulated using the Flow 3D program, as well as analyzing the most important characteristics of the hydraulic jumps for the negative step in a rectangular, horizontal and prismatic channel, and through the comparisons shown in the above Figures (3,4,5,6, and 7), between the results from the Flow 3D program and the results of Hagar's practical experiments, it was found that the results of the Flow 3D program were similar to a large extent with the results of Hagar's practical experiments with a very small error rate, and that error rate according to Figure 4, is about (-10%), so the Flow 3D program can be used with a correction factor by multiplying the results of initial flow depth for hydraulic jump (h1*1.10), and this will improve the similarity of the results to make the error rate about (± 10%) and this is an acceptable percentage in applications.

6. Notations

Symbol	Definition	Unit
B	channel bed width	m
F_1	Froude's number at the initial flow depth for hydraulic jump	
F1 ex.	Froude's number at the initial flow depth for hydraulic jump for Hager's experiments and Flow 3D model	
F1(th.)	Froude's number at the initial flow depth for hydraulic jump using equation (1)	
F_2	Froude's number at the sequent flow depth for hydraulic jump	
g	gravitational acceleration	m.s^{-2}
h_1	initial flow depth for hydraulic jump	m
h_2	sequent flow depth for hydraulic jump	m
$h_{max.}$	maximum flow depth of wave	m
E	energy head	m
Δ*E*	energy loss	m

L_J	jump length	m
q	discharge per unit width	$m^2.s^{-1}$
Q	discharge	$m^3.s^{-1}$
s	step height	m
$S= s/h_1$	relative step height	
V	average flow velocity	$m.s^{-1}$
$Y= h_2/h_1$	sequent depth ratio	
$(Y+S)_{max}=$ $(h_{max}+s)/h_1$	relative maximum wave height	
α	angle of step inclination	

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