STEPPED SPILLWAY HYDRAULIC MODEL INVESTIGATION

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ABSTRACT

An experimental hydraulic model investigation was conducted to evaluate the performance of a stepped overflow spillway . The spillway tested has a standard ogee profile with continuous steps cut into a straight portion of downstream face from tangential point (P.T) to the toe . Five constant dimensions (h/l=1.4) steps were used . The objectives of the study are to evaluate the effectiveness of steps on the amount of energy loss under nappe , transision and skimming flow regime . A preliminary comparison with a standard spillway (WES) , that the average increase in energy dissipation at toe is approximately 37% , that would imply a significant reduction of the size of downstream stilling basins . The experimental results indicate that dissipation is highest for the small values of y_c/Nh tested (i.e at nappe to transition flow) , also the dissipation ratio increase with increasing N . However , the results are compared to the earlier investigation , for commonly used ranges of the steps and flow condition a general relation is established between the energy

loss and the parameter y_c/Nh , which may be useful as a predictive formula in a practical applications .

NOTATIONS

d = vertical depth of flow over brink of step ;

H = depth of water above crest ;

H1 = local energy head above chosen step ;

Ho = upstream head referred to step elevation ;

h = step height ;

ΔH = difference in energy elevation between upstream and downstream ;

l = step width ;

N = number of steps from P.T ;

Q = discharge ;

q = discharge per unit width of spillway crest ;

V = approach velocity ;

Vl = local mean velocity ;

Vtoe = mean velocity at toe of spillway (downstream) ;

Y` = elevation difference between chosen step and crest of spillway ;

Ytoe = vertical depth of flow at toe ;

y = depth of flow normal to spillway slope , $y=d\cos\theta$;

y_c = critical depth ; and

θ = angle of downstream face of spillway to horizontal

INTRODUCTION

Stepped channels and spillways have been used for centuries . Recent advances in technology have permitted the construction of large dams , this need the development of new design and construction techniques particularly with flood facilities and safe dissipation of the kinetic energy of the flow[1].

The steps produce considerable energy dissipation along the chute or spillway and , thereby , reduce the size of the required downstream energy dissipater basin . Usually , the crest of overflow spillway follows the standard shapes that were determined at the U.S.Waterways Experiment Station , WES[2].

The flow accelerates along the downstream face and high velocities are attained at the spillway toe , that is lead to need a large energy dissipaters . Potentially high energy dissipation on stepped overflow spillways would imply a significant reduction of the size of downstream stilling basins .

The stepped channel design has been used for more than 3500 years . It is used by Greek, Roman, Moslem and Spanish engineers[3]. Recently, new construction materials (e.g. RCC , Roller Compacted Concrete) ,strengthened gabions has increase the interest for stepped channels and spillways . Many spillways of dams has been designed and constructed as a stepped spillway such as , Monksville dam which is part of the Wanaque South project being developed by the North Jersey District water supply Commission and the Hackensack water company . This is a modification of the WES standard profile for an uncontrolled ogee spillway[4] .

Limited experimental research in the past dealing with this problem , Sorensen[4], has suggested that considerable energy dissipation may take place on stepped surface of the spillway . Rajaratnam[5], proposed a theoretical estimate for the energy loss due to the steps . Peyras et al. [6], presented experimental results for small gabion weirs with flat crest and up to seven steps .

Christodoulou[7] , adopted with experimental program the comparison between WSE and stepped spillway with moderate number of steps , he calculate the amount of energy loss under skimming flow conditions . Chanson[1], presented a reviews of the hydraulic characteristics of modern stepped spillways by describing the flow patterns at skimming flows. Chanson et al. [8], explained by experimental study the transition flow regime feature on stepped chutes , the results provide a characterization of air concentration , velocity and bubble count rate distribution .

The aim of present study is to examine by the experimental work the ability of stepped spillway on energy loss under three flow regime , Nappe flow at low flow rates , transition flow and skimming flow regime at larger flow rates ,but the focus were on the transition flow regime . The results were analyzed and compared with the previous investigators findings , the basic equation are developed .

EXPERIMENTS

The experiments were conducted at the Applied Hydraulic Laboratory of the Technical Institute of AL-Najaf . The spillways tested had the form and dimensions shown in Fig.(1) , in which all dimensions are given in centimeters . The steps are designed so that the envelope of their tips indicated by broken line , follows the standa with the stepped spillway , where , the steps is begins from the tangential point (P.T) (i.e at the straight portion of the spillway downstream face) up to a toe . Five steps on a straight part with constant width (l=2.5cm) and height (h=3.5cm) , to give a constant height to width ratio (h/l=1.4) . This ratio taken as adopted by Christodoulou [7]. The spillway was made of galvanized steel coated to avoid warping . It was placed in laboratory flume 10m long and 0.42m wide, beyond the toe of the spillway the flume had zero bottom slope and there was no downstream control . The discharge supplied were measured by flow meter connected with supply pump . The disharge used range from 73 l/min up to 350 l/min . The measurements taken from each run by using point gauge were ; depth of flow at 0.5m distance upstream of spillway , at the crest , at the toe (downstream) and at the tip of the first four steps . Table(1) shows the experimental measurements .

FLOW PATTERNS

The facilities were designed to operate with flow conditions ranging from nappe to skimming flow regimes . Although the focus of the study was on the transition flow regime , the low discharges flowed down the spillway distinct free falling Nappes (Runs 1 and 2) , for larger discharges (Runs 9 and 10) , the flow skimmed over the pseudo-bottom formed by the step edges , so that all cavities were eliminated . At low flows (i.e Nappe flow regime) , the total fall is divided into a number of small free falls.

The energy dissipation occurs by jet break up in air ,by jet impact on the step , and possibly with the formation of hydraulic jump on the step[1]. At this flow range the step height is to be considered relatively large for nappe flow .

For a given step geometry , an increase in flow rate give an intermediate flow pattern between nappe and skimming flow , this pattern is well known , transition flow regime . The transition flow is characterized by a pool or recirculating water with small air cavity immediately at the beginning of a step , this is called by Chanson[1], a stagnation point , after this point a spray region is begin at which a free surface aeration was observed.

Downstream of the spray region , the supercritical flow is decelerated up to the downstream step edge . In transition flow , the free surface exhibited an undular profile in phase , this observation were well compatible with the aforementioned by Chanson[8].

In skimming flow regime (Run 9 and 10) , the water flows down the stepped face as a coherent stream , skimming over the steps , the air cavities are diminished or absent , the flow surface over the steps appearance as a quasi- smooth occurred at WES spillway . At this flow regime the external edges of the steps form a pseudo bottom over which the flow skims , also it is observed that the flow characterized by air entrainment .

PREDICTION OF THE FLOW REGIME

The type of stepped flow regime is a function of the discharge and step geometry , due to a limiting experimental data , the writer adopted the following expression as used by Chanson[1] to predict a changes in flow regimes .

The upper limit of nappe flow may be approximated as :

$$y_c/h = 0.89 - 0.4\, h/l \qquad (1)$$

While the lower limits of skimming flow may be estimated as :

$$y_c/h = 1.2 - 0.325\, h/l \qquad (2)$$

The Eq.(1) refer that the flow regime can be considered the end of nappe flow and beginning of transition flow , whereas , the Eq.(2) , refers that the skimming flow is more affect .

ANALYSIS OF RESULTS

This study describe interesting observations of energy loss on stepped spillway based on laboratory experiments and attempt to establish the relation for energy loss in terms of number of steps , N ; geometry of steps , h and l ; and the discharge which expressed in terms of critical depth , y_c . Also a comparison with WES spillway has been presented to show the validity of stepped face spillway on reduce the residual kinetic energy downstream . Referring to the notation shown in Fig.(1) and appendix II , the total head loss up to a certain step is expressed by :

$$\Delta H = Ho - H1 \qquad (3)$$

In the present study the ratio h/l was 1.4 , this value is close to the practically applied as adopted by Christodoulou[7] . The importance of the parameter y_c/h was earlier adopted by investigators , Sorensen [4] , Rajaratnam[5] , and others . A preliminary comparison , that the average increase in energy dissipation at toe due to using five steps instead of flat surface of WES spillway is approximately 37% , that lead to ability of reduction in stilling basin structure size at the same percent.

According to the previous studies , this percent reduction of kinetic energy will increase with increasing the number of steps . The present study also demonstrate this fact , where $\Delta H/Ho$ increase with increasing N , see Fig.(2) . However , as can be seen from Fig.(2) , the flow regime has appreciable effect on energy dissipation . There is high energy dissipation for small y_c/h (i.e Nappe flow regime) , apparently due to the more pronounced effect of the steps for small water depths relative to the step size . At this situation the flow from each step hits the step below as a falling jet , the larger amount of energy dissipation may be attributed to the formation of hydraulic jump on each step . Although the Nappe flow regime are evidently most efficient in terms of energy dissipation , they are not likely to be sought in practice due to the anticipated considerable damage of the stepped structure[7] but may apply to relatively low flow rates . When the flow regime is fully developed to a skimming situation the percent reduction of kinetic energy will be at low amount (see Fig.(2)) , however the trend of increasing in dissipation is more pronounced at skimming flow as can be seen from Fig.(3) . This may be attributed , that the coherent stream above steps faces approaching to a flow over a flat face of WES spillway leading to minimize the percent increase of kinetic energy dissipated . The increasing of the trend as the skimming flow developed was due to the aeration of a free surface by a strong air entrainment , where , the steps may be considered as a macroroughness of the boundary at a scale much larger than the usual wall roughness of a flat surface at WES spillway .

EXPRESSION FOR ENERGY LOSS

If uniform flow conditions are reached at the downstream end of the spillway , Sandip P. Tatewar et al.[9] , showed that the total head loss can be written in terms of the y_c /Nh . The authors adopted the ogee weir formula to express the discharge over the spillway to present the following expression for the ratio of energy loss after simplification using algebraic manipulations :

$$\Delta H/H_o = 1/\left(1+C(y_c/Nh)\right) \qquad (4)$$

Where C would vary from 1.273 to 1.4 . If using the average value of C that is equal to 1.34 , Eq.(4) can be rewritten using multi – regression with ($R^2 = 0.99$) as :

$$\Delta H/H_o = 0.577(y_c/Nh)^2 - 1.07(y_c/Nh) + 0.98 \qquad (5)$$

The present study adopting a theoretical expression of Eqs.(4 or 5) for the ratio of energy loss to verifying the experimental finding . Fig.(4) , demonstrate the comparison between Eq.(5) and experimental results , where the ratio of energy losses is plotted as a function of y_c/Nh . In this figure the observation refer that the same trend between theoretical and experimental data , but Eq.(5) is less conservative where, it predicts higher energy loss compared with experimental results. Accordingly and with best regression analysis , it may be adopting the following formula which give (R^2=0.94) as a predictive equation of the ratio of energy losses at any step of spillway that is :

$$\Delta H/Ho = 0.88(y_c/Nh)^2 - 1.5(y_c/Nh) + 0.9 \qquad (6)$$

It should be noted that the model of Eq.(6) is subjected to the stated limitations where , it used just with the steps which is forming a straight downstream portion of a spillway ; facing slope with downstream channel is 55^o ; and the flow regime between Nappe and skimming . When the flow regime approaching a skimming , an analysis indicate a large scatter between Eq.(6) and experimental data that is refer to a less correlation , see Figs.(4 and 5) .

CONCLUSIONS

Experiments on a laboratory stepped spillway indicate that the energy dissipation may be significantly greater than this observed by using WES spillway . By using five steps on a straight portion of the downstream face of spillway with constant width l=2.5cm , and height , h=3.5cm , the percent increase in kinetic energy dissipation were 37% . It is found that the energy loss due to the steps depends on the ratio y_c /Nh where as N increase the dissipation of kinetic energy increases . However , as y_c/h decreases near the limit of Nappe flow , the dissipation ratio increase . On the other hand , the trend of dissipation was more appreciable as a skimming flow developed . In a present study the flow is mainly located within a transition regime , by analyzing the results , the predictive model extracted , may be used to calculate the amount of kinetic energy ratio dissipated downstream of stepped spillway . It should be noted that the predictive model , generalized to use at a specified conditions with transition flow regime , hence , the usage for others have a considerable caution .

Acknowledgments

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Table(1) : Experimental data measured using Point gage

Run	Discharge (l/sec.)	Standard Spillway		Stepped Spillway					
		H cm	Ytoe cm	H cm	Ytoe cm	d1 cm	d2 cm	d3 cm	d4 cm
1	1.2	1.38	0.48	1.39	0.71	0.70	0.78	0.81	0.85
2	1.7	1.76	0.59	1.60	0.88	0.87	0.91	1.01	1.03
3	1.9	1.86	0.62	1.80	0.93	0.92	0.94	1.06	1.12
4	2.5	2.25	0.79	2.27	1.17	1.17	1.19	1.20	1.21
5	2.7	2.36	0.81	2.30	1.22	1.22	1.23	1.25	1.27
6	3.8	2.97	1.04	3.00	1.61	1.60	1.61	1.63	1.65
7	3.9	3.02	1.06	3.15	1.66	1.59	1.60	1.67	1.68
8	4.6	3.36	1.15	3.39	1.83	1.82	1.84	1.84	1.85
9	5.4	3.72	1.21	3.70	1.92	1.90	1.91	1.91	1.92
10	5.8	4.00	1.30	3.99	2.10	1.91	1.94	1.98	2.00

Table(2): Analysis of Experimental data

Run	y_c cm	y_c/h	$\Delta H/Ho$		y_c/Nh (Stepped Spillway)			
			Standard Spillway	Stepped Spillway	Step Number (N)			
					1	2	3	4
1	0.93	0.266	0.775	0.879	0.266	0.133	0.089	0.066
2	1.18	0.337	0.707	0.846	0.337	0.168	0.112	0.084
3	1.25	0.357	0.674	0.831	0.357	0.178	0.119	0.089
4	1.54	0.440	0.654	0.812	0.440	0.220	0.147	0.110
5	1.59	0.454	0.621	0.801	0.454	0.227	0.151	0.114
6	2.04	0.538	0.550	0.771	0.583	0.291	0.194	0.146
7	2.07	0.591	0.544	0.772	0.591	0.296	0.197	0.148
8	2.31	0.660	0.474	0.745	0.660	0.330	0.220	0.165
9	2.58	0.737	0.363	0.698	0.737	0.368	0.246	0.184
10	2.70	0.771	0.367	0.703	0.771	0.386	0.257	0.193

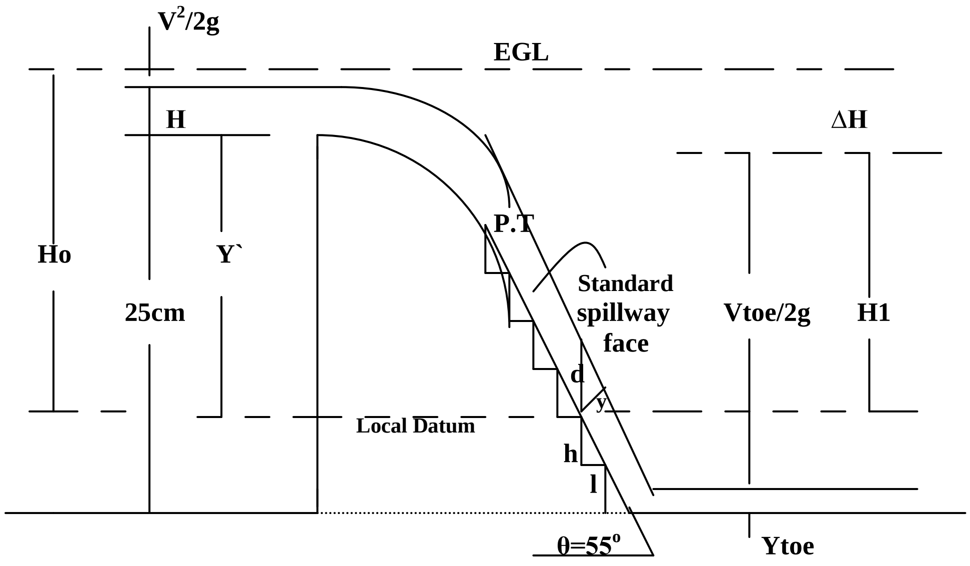


Fig.(1) : Schematic diagram of Stepped Spillway tested

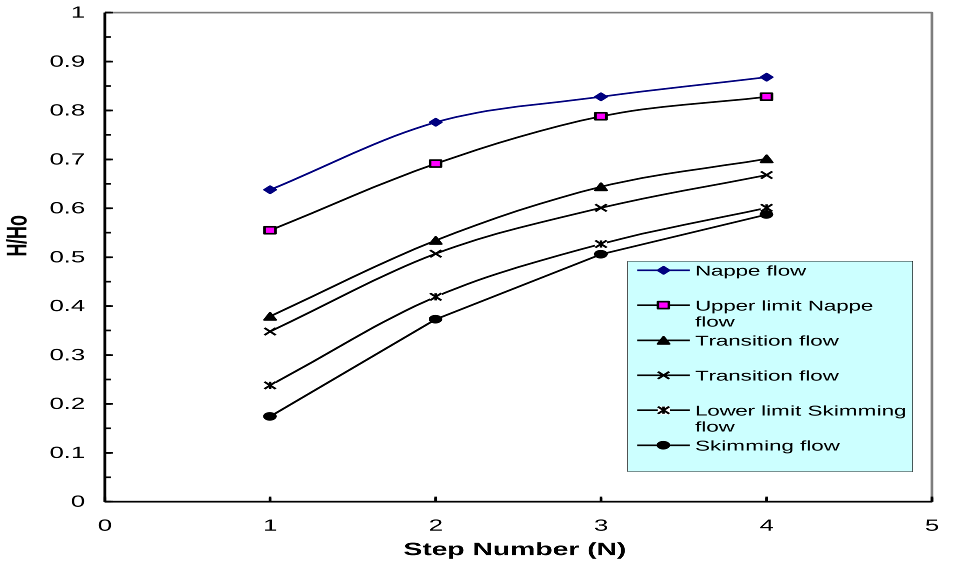


Fig.(2): Effect of step number and flow regime on energy dissipation

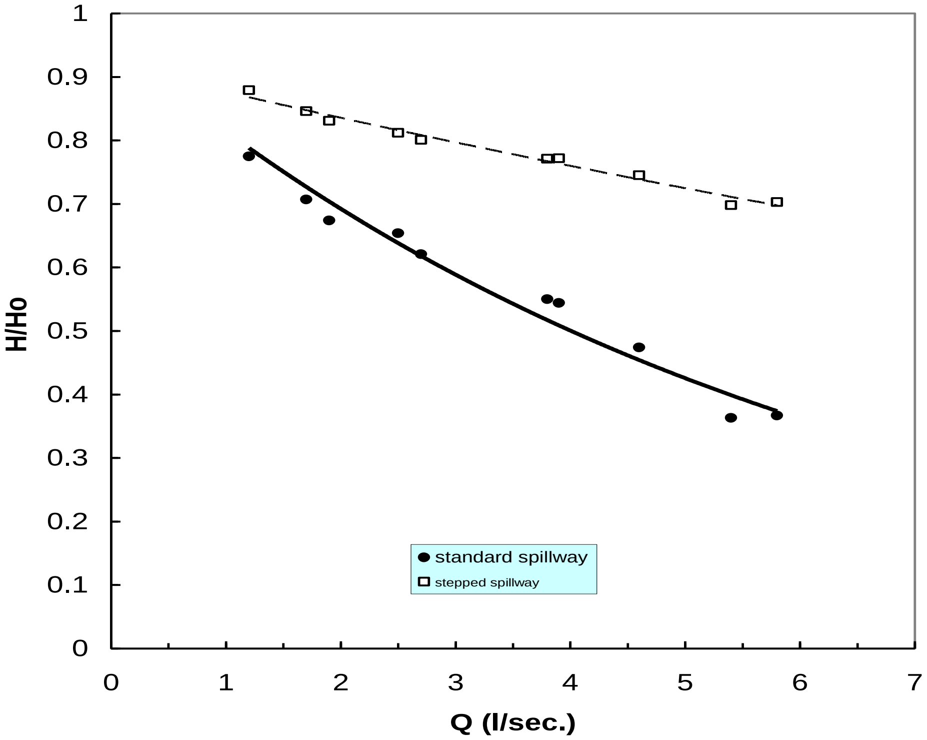


Fig.(3): Comparison of dissipation of kinetic energy between WES and stepped spillway

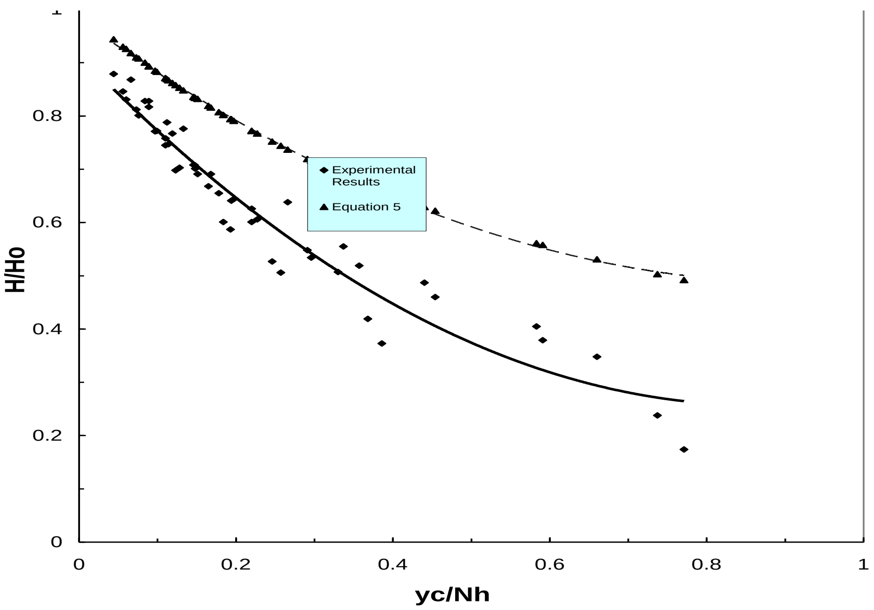


Fig.(4): Comparison between experimental data and Eq.5

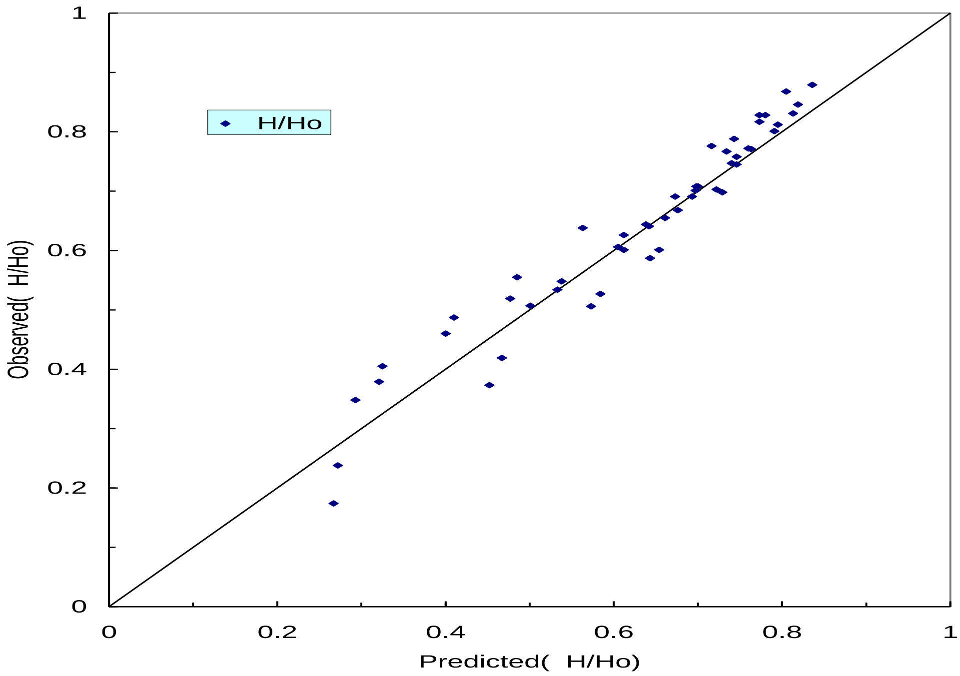
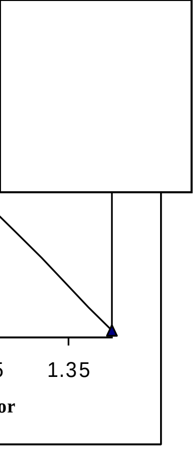


Fig.(5):Verification of model Eq.6 with experimental data



دراسة موديل لمطفح هيدروليكي منحدر

د. جعفر صادق معتوق

مدرس

قسم هندسة البناء و الإنشاءات–الجامعة التكنولوجية

الخلاصة

اتخذت هذه الدراسة نتائج العمل ألمختبري التي أجريت على نموذج هيدروليكي لمطفح مدرج للمقارنة مع نتائج المطفح القياسي . أن النموذج المتخذ للدراسة يحتوي على خمسة تدريجات ثابتة الأبعاد نفذت على طول الجزء المستقيم من وجه المطفح عند المؤخر أبتداءاً من نقطة التماس (P.T) وحتى قدمة المطفح لتعطي نسبة الارتفاع إلى العرض (h/l=1.4) . أن الغرض من الدراسة هو بيان فعالية وجود التدريجات على كمية الطاقة الحركية المبددة عند المؤخر ومن خلال ثلاثة أنظمة جريان مختلفة أن التقييم الأولي للنتائج يشير إلى أن نسبة الزيادة في تبديد الطاقة الحركية عند المؤخر (Toe) هي 37% مقارنة بتلك المسجلة عند استخدام المطفح القياسي . كذلك فأن النتائج المختبرية أشارت إلى أن التبديد في الطاقة الحركية يزداد كلما أقترب نظام الجريان من الجريان غير المغمور (Nappe) أي كلما تناقصت النسبة y_c/ Nh . من ناحية أخرى فأن زيادة التبديد في الطاقة الحركية تتناسب طردياً مع الزيادة في عدد التدريجات N . أن النتائج المختبرية تم مقارنتها مع دراسات سابقة ولظروف جريان مماثلة أو متقاربة وبالتالي تم التوصل الى استنباط علاقة رياضية يمكن أن تستخدم لحساب نسبة التبديد في الطاقة الحركية للجريان فوق مطفح مدرج ولظروف جريان محددة .