PHYSICAL AND NUMERICAL STUDY OF INWARD TRAPEZOIDAL PROPORTIONAL LINEAR WEIRS

ETUDE PHYSIQUE ET NUMERIQUE DES BARRAGES TRAPEZOÏDAUX PROPORTIONNELS LINEAIRES INTERIEURS

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ABSTRACT

Linear proportional weirs are defined as a sharp-crested weir in which the discharge is linearly proportional to the head over the weir crest and have high accuracy compared with non–linear ones. In this study a linear proportional weir of simple geometric shape in the form of an inward trapezium was studied using physical & numerical model. The linear proportionality of the flow over these weirs was investigate. Finally, these weirs were simulated by Fluent software. The main objective of this work is approach to a linear head-discharge relationship, and simulated the flow by means of a three dimensional (3D) numerical model.

The experiments were conducted in a metal-glass flume of rectangular cross section. The flume has the dimension of 0.25m width, 0.5m depth, and 10 m length with a slope of 0.002. The flume is equipped with a sluice gate at the entrance and discharge was measured by a triangular weir placed at the end of it.

In this study 3-dimential numerical simulation of inward trapezoidal was evaluated using third turbulence k - ε models.

The free surface location is computed using the VOF (volume of fluid) method. The results showed that for different side slopes, the weirs have linear function about 74% of their height.

For each weir, a linear height-discharge equation and performance range is presented. Numerical simulation of flow over weirs showed that between turbulent k - ε models, the Realizable type has the minimum error among the other models and the average relative errors in the upstream water depth and depth on the crest were 3% and 5%, respectively.

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The combined experimental and numerical study highlights the importance of this weir of simple geometry, which has a linear head-discharge relationship within certain ranges of head and permissible percentage errors in discharge computation.

Key words: Hydrometry, Linear proportional weir, Physical model, Kinetic energy.

RESUME

Les barrages linéaires proportionnels sont des barrages dont la paroi est pointue, dans lesquelles la décharge est linéairement proportionnelle à la tête sur la crête du barrage et qui ont une grande précision par rapport aux barrages non-linéaires. Dans cette étude, un barrage linéaire proportionnelle de forme géométrique simple, sous la forme d'un trapèze l'intérieur, a été étudié en utilisant un modèle physique et numérique. La proportionnalité linéaire de l'écoulement sur ces barrages avec des pentes latérales différentes a été étudiée. Enfin, ces barrages ont été simulés par le logiciel Fluent. L'objectif principal de ce travail est une approche à la relation de tète-décharge linéaire. L'écoulement est simulé au moyen d'un modèle numérique tridimensionnel (3D).

Les expériences ont été menées dans un canal en métal-verre, de section transversale rectangulaire. Le canal mesure 0,25m de largeur, 0,5 m de profondeur, et 10 m de longueur avec une pente de 0,002. Le canal est équipé d'une bonde à l'entrée et la décharge a été mesurée par un barrage triangulaire placé au bout de celui-ci.

Dans cette étude, la simulation numérique tridimensionnelle des trapézoïdes intérieurs a été évaluée en utilisant les modèles k-ε troisième turbulence.

L'emplacement de surface libre est calculé en utilisant la méthode VOF (volume de liquide). Les résultats ont montré que pour des pentes latérales différentes, les barrages ont une fonction linéaire d'environ 74% de leur hauteur.

Pour chaque barrage, une équation linéaire hauteur-décharge et une gamme de performance sont présentées. La simulation numérique de l'écoulement sur les barrages a montré que : entre les modèles k – ε de turbulence, le Type réalisable a l'erreur minimale parmi les autres modèles ; et les erreurs moyennes relatives dans la profondeur de l'eau en amont et en profondeur de l'eau sur la crête étaient de 3% et 5%, respectivement.

L'étude d'ensemble, expérimentale et numérique, met en évidence l'importance de ce barrage de forme géométrique simple. Ce barrage a une relation linéaire tête-décharge dans les limites de certaines gammes de tête et celles du pourcentage d'erreur admissible dans le calcul de décharge.

Mots clés: Hydrométrie, barrage linéaire proportionnel, modèle physique, énergie cinétique.

1. INTRODUCTION

Flow measurement or hydrometrics has long been studied by hydraulic engineers and multiple methods have been innovated in this regard. Trapezoidal and triangular weirs are used to

measure the flow in open channels. In such weirs, discharge is non-linearly proportional to the head over the weir; therefore the figure of discharge-head is curvilinear, while in linear weirs head-discharge relationship is line with constant slope. Thus, the accuracy of linear weirs is more than non-linear weirs (Kschua Morti and Gridhar: 1989).

Linear proportional weir was first introduced by Stat and then modified as an applied device by Satro in 1908 which is today known as "Satro" weirs (Morti and Gridhar: 1989).

Given the importance of high accuracy, the simplicity of form and easy installation of flow measurement structure, much research has been conducted on different types of weirs including linear weirs. The researches have been based on hydraulic experiments on physical models or methods of numerical optimization. Keshva Murthy and Giridhar (1989) have proposed two methods to determine linear head-discharge relationship for inclined triangular weirs"IVN" (a type of linear weir). In the research described in this paper, another type of linear weir has been studied based on numerical and Physical model. This is called linear proportional trapezoidal weir, as the head-discharge relationship in this weir is linear. The difference between this weir and inclined triangular weirs is that there is no head constraint, therefore construction and installation of this weir is simpler than inclined triangular weirs. On the other hand, given the progress of computer sciences and simulation software in water related sciences, it is necessary to plan a proper method to simulate the linear weirs. 'Fluent' is one of the simulation software which has been adopted in water sciences researchers recently and for the present study also.

Linear Proportional Weirs

In general, weir discharge is expressed by: $Q \propto H_d^{\,n}$. If the weir is designed in a way that discharge changes linearly corresponding to H_d changes (n = 1), the weir is called proportional. In fact the discharge passing these weirs is linearly proportional to water head over weirs. These weirs are used as controller in water divider systems, and also as structures of flow measurement and trappers of residue in stream openings. Linear proportional weirs have higher accuracy with minimum error, as compared to rectangular and triangular weirs in similar situations.

2. MATERIALS AND METHODS

The purpose of this research is to determine linear discharge-head relationship for Inward trapezoidal weirs. Experiments have been conducted in flume of 9 m length and 2.5 m width. Linear proportional trapezoidal weir was tested in vertical and inclined mode relative to direction of flow with respect to their H – Q relation. The angle of inclination of the weir relative to the flow direction has been 30 and 60 degree against the vertical line.

Five points of measurement have been chosen in the length of weirs in order to investigate the profile of water surface. A sharp-crested triangular weir has been used to measure the flow discharge.

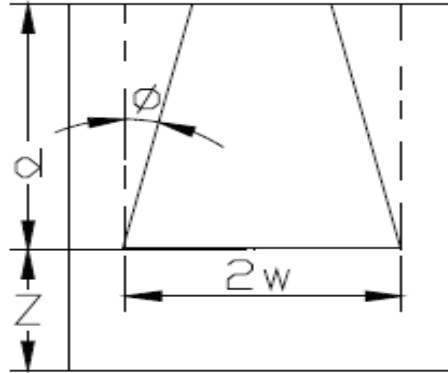In this research the weirs are made of PVC sheets thickness of 3 millimeters.
Figure (1):

Fig. 1. Trapezoidal weirs section

ϕ Is angle of side slopes,

2*w* is the length of weir crest,

d is the whole height of weir from the edge of crest to top and z is the height of weir crest.

The equation of trapezoidal weirs is:

$$Q = \frac{2}{3} cd \sqrt{2g} \, (2w) h^{1.5} - \frac{8}{15} cd \sqrt{2g} \, \tan\frac{\phi}{2} h^{\frac{5}{2}}$$

(1)

cd = Coefficient of discharge;

h = Head above the Crest;

g = Acceleration due to gravity

Numerical model

In this research by solving the equations of continuity and momentum and using turbulence models, the methods of multi phase flow and finite volume and algorithms of concurrent solving, flow pressure velocity has been simulated in model of inclined trapezoidal weirs. Volume of fluid (VOF) The water surface location was determined with the volume of fluid (VOF) method.

The VOF method uses a function F(x, y, t) to assign the free surface. The function F is obtained from the following equation:

$$\frac{\partial F}{\partial t} + u_j \frac{\partial F}{\partial x_j} = 0$$

A unit value of F corresponds to a cell full of fluid, while a zero value indicates that the cell contains no fluid. Cells with F values between 0 and 1 contain a free surface.

The model of fluid volume has been used to simulate the multi phase flow and the turbulence model of $k - \varepsilon$ standard, RNG and realizable methods have been used to simulate the turbulent flow. The method of Finite volume has been used to solve related equations. The model of Non-equilibrium wall function has been used to analyze wall flow.

As the flow is a function of walls in turbulent flows, the analysis of flow near the walls is of high importance to have proper velocity profile. The methods of flow simulation near the wall are of two types. In the first method, the inward layer is not analyzed but semi-empirical relations from near wall is generalized to outward layer which is called wall function method. In the second method, the inward layer is analyzed and then the outward layer is analyzed which is called near wall treatment method. In the second method, since a lot of elements are needed in slimy substratum, the time and expense of computations increases significantly. Therefore the model of non-equilibrium wall functions has been used to analyze the side wall flow which is a subdivision of the first method.

Turbulent kinetic energy, depreciation rate of kinetic energy, and method of second order upstream split have been used for momentum equations. The method of geometric reconstructing is used for volumetric fraction equation and method of PRESTO shall be used for pressure equation. At the beginning of flow, small under relaxation coefficients between 0.1 to 0.15 was used due to relatively difficult convergence. After progression of flow time, the coefficients of under relaxation increased gradually which finally with the maximum time pace of 0.005 seconds, increased from 0.8 to 1.

In order to simulate models, borderline entrance pressure has been used for a surface, entrance velocity for b surface, exit pressure for d, c surfaces and borderline wall shall be used for e surface.

The outline of Boundry Condition has been defined and the grid weir shall be respectively displayed in figures(2),(3).
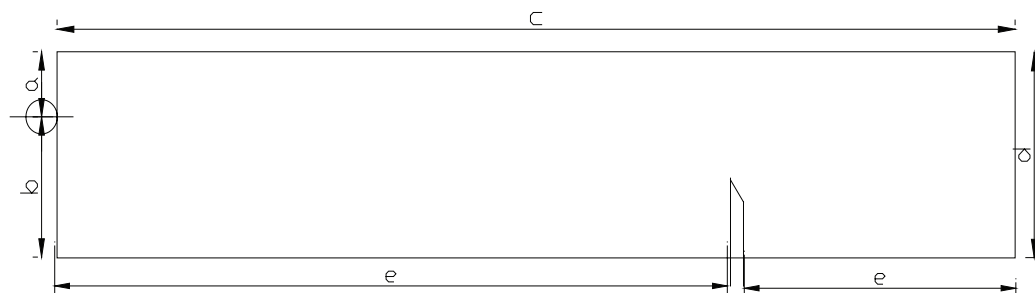

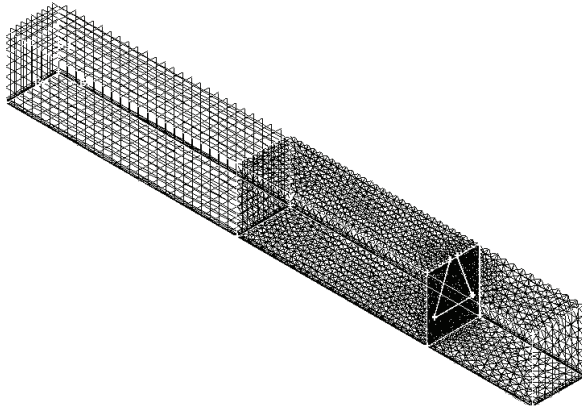Fig 2. Outline of borderline cases defined in the model

Fig 3. A three-dimensional preview of grid weir

Finally the grid model with borderline cases transferred to fluent software with the format of msh. Triangular elements of Pave type and quad lateral elements of Map type have been used to make grid of sheets. Different models have been used to make grid of volumes, for example the element of hex/wedge of cooper type has been used in frame of weir, and the element of hybride/tet of TGrid type has been used to make grid of other upwind and downwind volumes. Figure (3) display a sample of grid range. Four grids with 70000, 50000, 38000 and 100000 elements have been allocated to this model. Results show that there were no large discrepancy between the results of model and the number of elements 50000, 70000 and 30000. However as the number of elements reduced to 38000, the errors increased significantly compared with physical model. Therefore in all models, the same grids with approximate number of 38000 computational elements were used.

3. CONCLUSIONS

In this section, the results shall be discussed and investigated according to experiments conducted and theoretical principles.

As it was discussed in the previous chapter, the profile of water surface at all models in 5 to 8 different discharges has been measured. The results are explained in figures (4) and (5).
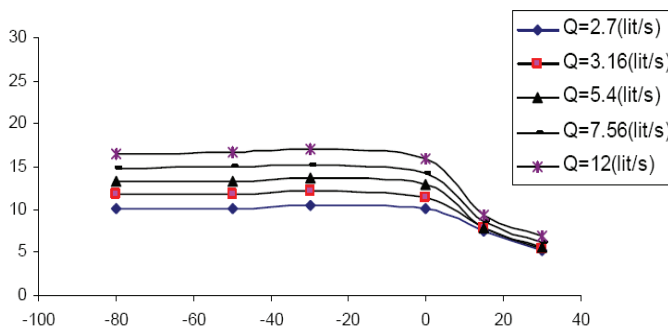

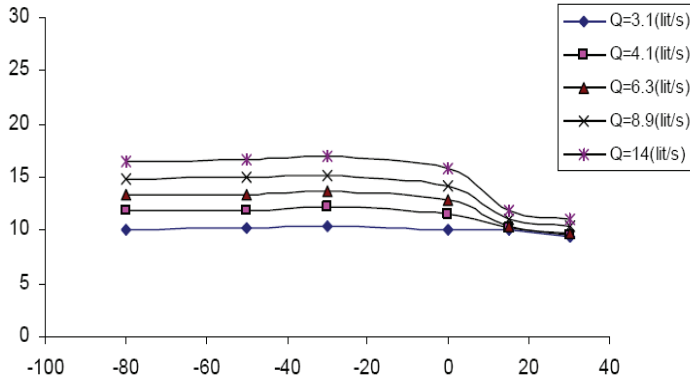Fig 4. Water surface profile in normal weir

Fig 5. Water surface profile in inclined weir

According to these figures, in entrance section of weir "near and above the crest", the water surface will reduce. In other words, weir in channel functions as a barrier and reduces the energy of flow. According to curve of under critical flow energy in upstream section of weir, fall of energy causes fall of depth and accordingly the water surface. Profile of flow in this range is of M_2 type. In the downstream crest where flow falls, the profile of water surface changes in proportion with angle of weir against downstream. When weir is in vertical mode, the fall of flow and accordingly the maximum curve of flow lines shall be observed. Inclining weir toward downwind reduces the curvature of flow lower nappe and accordingly increases the flow passed over weir. According to figure (4) increasing the angle, the inclination of weir toward downwind flow of passing discharge shall also increase. In other words, the increase of weir inclination reduces the contraction of flow lower nappe. In addition, linear performance of weir trend shall be preserved in the balanced mode. The effect of surface elasticity is less obvious in lower depths (Bass: 1989), therefore to reduce the effect of surface elasticity over flow, the measurement of flow shall start from a minimum amount and non-zero.

Discharge-head figures on trapezoidal weirs obtained from experiments have been displayed in figures (6) and (7).
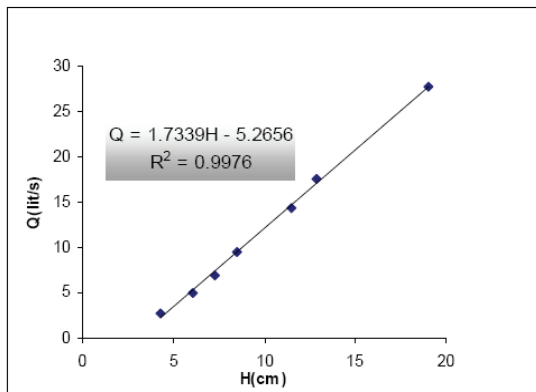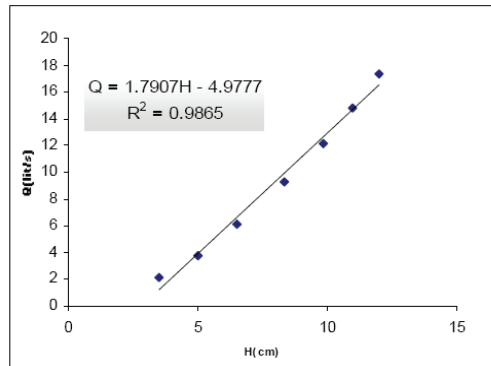

Fig 6. Actual Discharge Versus head in normal weir

Fig 7. Actual Discharge Versus head in inclined wier

Discharge-head relation with relatively high coefficient implies the linear discharge-head relation in a large range of flows in trapezoidal suppressed weirs. Finally the experiments show that these weirs in 73% of their height have linear characteristics. The linear range starts from 0.22 weir head to 0.95 weir head. The figures (6) and (7) display respectively the discharge-head figure of reversed trapezoidal weirs for normal and inclined position .The following proportions shall be used to calculate discharge coefficient:

$$Cd = \frac{q_{act}}{q_{th}} \qquad (1)$$

$$C'd = \frac{q_l}{q_{th}} \qquad (2)$$

In which, the width of crest is (2*W*) = 18 cm.

The linear relation defined for each weir is q_L.

The figure (8) and (9) displays the amounts of *Cd, C'd* using the relations (1) and (2)
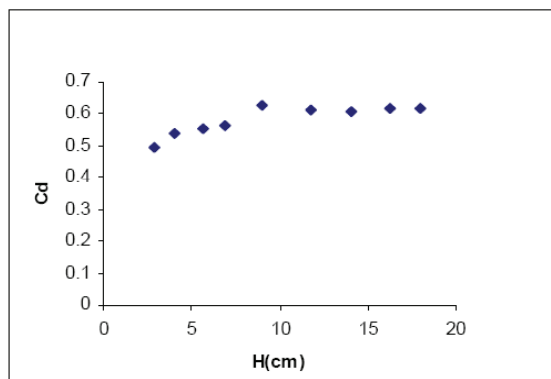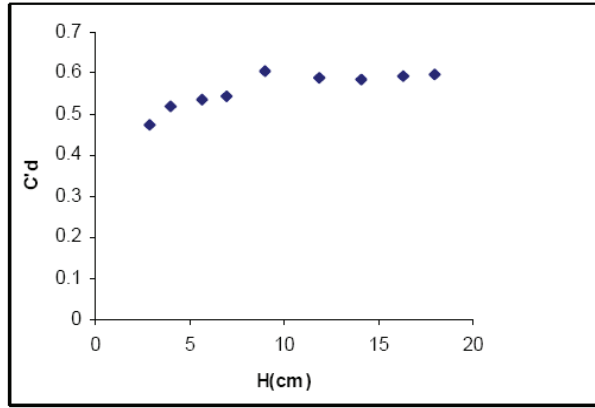

Fig 8. Amount of C'd using (1)

Fig 9. Amount of C'd using (2)

According to this figure, discharge coefficient in initial depths has increased and eventually will be fixed. As it is evident in the figure, there is little discrepancy of 1.5% between theoretical and laboratorial amounts which imply the accuracy of proposed relation for this weir. The average discharge coefficient in weirs with positive wall slope is fixed and is respectively 0.63 and 0.61, using the theory equation and the linear relation defined for weirs.

Analysis of numerical model results

In this research, the $k - \varepsilon$ turbulence models including *Rng, Realizable* and also *simple* solving algorithms have been used to find a proper model for flow simulation.

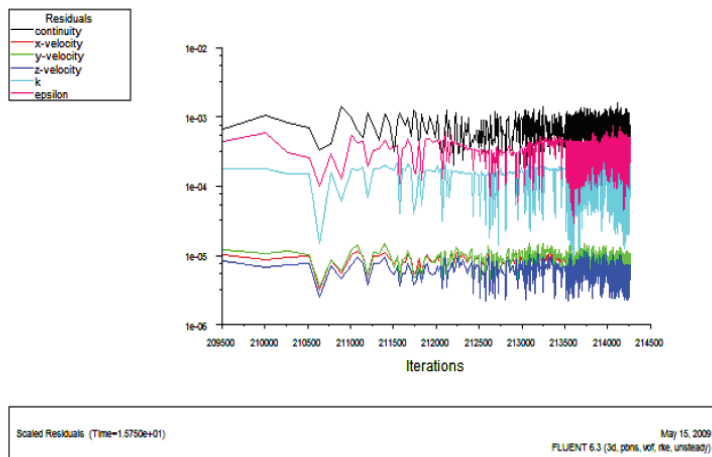The relative error of numerical model in different modes has been expressed by percentage in figure (10)

Fig 10. The relative error (percentage) of numerical model in different modes

In three dimensional models conducted so far, the relative error of *standard* method has been more than *RNG* method. The relative error of *Realizable* method is virtually the same as *RNG* method. Therefore given the instability of *Realizable* method in comparison with *RNG* method, *RNG* method was used for simulation.
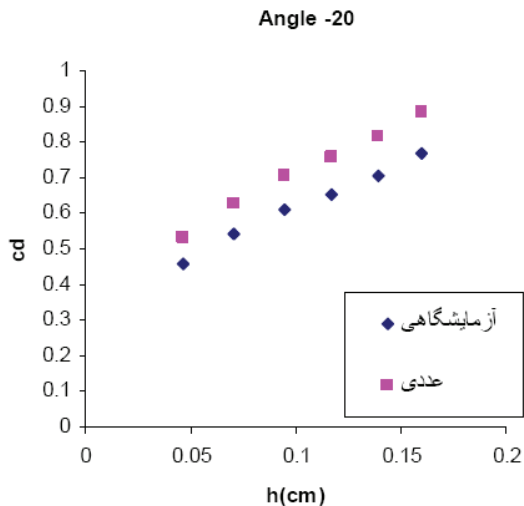
Angle -20

Fig 11. Compares the numerical and physical models

This figure displays the correspondence between results obtained from numerical simulation and physical experiments. The relative error of numerical model in simulation of water depth in upstream and downstream of inclined trapezoidal weir is between 3.01 to 3.4 percent. As it is observed, in exchange for a fixed discharge, the depth of flow in numerical model is less than physical model. The comparison between physical and numerical model implies a high correspondence. Therefore the physical models could be substituted by numerical models because of less expense and less time.

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