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Length Of Flow Separation

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Abstract— **Flow separation is a natural phenomenon encountered at some cases downstream of multi-vent regulators. The main flow is divided into current flow and dead zone flow (reverse flow and weak forward flow). The length of flow separation must be taken into consideration downstream of regulators for canal side's protection and accurate flow measurement. The present study aims to analyze the flow separation downstream of regulators in sudden expanding stilling basin. An extensive experimental program has been conducted on a regulator model of five vents at the Hydraulic Research Institute (HRI). Empirical model based on the results of the dimensional analysis is proposed within this study to compute the dimensionless length of separation by using multiple linear regression analysis. Results revealed that the empirical model proposed can be used for practical applications in canal side's protection and flow measurements downstream of hydraulic structures.**

Keywords— **separation of flow, length of flow separation, sudden expanding channel, hydraulic structures, and velocity vectors.**

Introduction

Previous investigations on rigid hydraulics of sudden expanding stilling basins proved that the flow patterns in such basins are asymmetric. An explanation of the asymmetric behavior of the subcritical flow in symmetric sudden expansion [1]. A predictive method was presented that agreed well with the experimental observations and extended the predictive method theoretically to correct measures up to a Froude number of 1.5. A new explanation for asymmetric flow patterns of the supercritical flow in symmetric sudden expansion was delivered [2], in which the hydraulic jump is one of the flow features. The explanation was shown to agree with available observations. Numerical approaches and experimental studies were used to analyze flow patterns for recirculating flows in sudden two-dimensional expansions [3]. The analytical results for low expansion ratio of 1.25 show to be in good agreement with those of experimental findings. For larger expansion ratios, experimental findings reveal that the flow patterns are asymmetric and unstable, because turbulence decay at faster rate after the points of reattachment, and flow attains symmetric conditions earlier.

Seemly few studies exist for the flow separation downstream of hydraulic structures. Such as the separation of flow in diversion channels that cause damages in the bed and sides of the downstream channels [4]. The results show that the use of a simple hump reduced the flow separation and limited the area in which the reverse flow occurs. This decrease in reverse flow contributes to the reduction of possible damage to the bed and sides downstream the channels. Although using the physical model study to evaluate the separation zones in such hydraulic phenomenon, a validation of an analytical method of the opposing flow condition is achieved [5]. There was a good agreement between analytical method and physical model. The validated analytical method approach can be used to predict the maximum width of the flow separation zone. An analytical tool was presented for using in assessing the potential for hydraulic jumps or chocked flow conditions in water distribution applications. While using the initial Froude number as the only dependent variable, the dimensionless length of flow separation may be considered as nearly independent of the longitudinal coordinate x. A formula for the dimensionless length of separation (*W/L*) which occurs for abrupt; 90° enlargement stilling basin was introduced [6]. While a statistical formula predicting the dimensionless length of flow separation (*W/L*) in a radial stilling basin was introduced [7]. later on an experimental study of the separation of flow in a sudden expanding stilling basin downstream of multi-vent regulators was studied [8]. The plane of separation is considered smooth solid boundary between the reverse and current flow, vertical from the water surface to the bed, and a part of circle. The assumption of the separation zone as a part of circle is particularly verified by plotting velocity vectors. The dimensionless length of flow separation (*W/L*) is dependent on the expansion ratio (*e*) and the inflow Froude number (F_1), and the effect of submergence ratio (*S*) can be neglected. Statistical model was developed based on the multiple linear regression, to predict the dimensionless length of separation.

A theoretical description of the separation zone between current flow and dead zone flow (reverse flow and weak forward flow) in a sudden expanding stilling basin downstream of multi-vent regulators, as a part of an ellipse is practically verified by plotting velocity vectors [9]. The results show that, the percentage area of dead zone to the area through length of separation depends mainly on the expansion ratio, with maximum value of 81% for operated side gates. A statistical analysis was derived, to predict the percentage area of dead zone flow to the area through length of separation.

It can then be concluded that there is not a direct relation between the dimensionless length of flow separation and maximum width of flow separation zone downstream of multi-vent regulators with sudden expanding stilling basin without considering the flow characteristics. Within this research work, a simple and applicable formula for computing the dimensionless length of flow separation was derived to predict the minimum protection length of canal

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sides and the minimum distance of flow measurement downstream of multi-vent regulators based on the maximum width of flow separation zone only.

Theoretical Study

I.Equationof plane of separation

According to Ref. [9], for simplicity, assume that the plane of flow separation is vertical and does not change from the water surface to the bed. The plane of separation is considered as a smooth solid boundary between the current flow and the dead zone flow (reverse flow and weak forward flow). Finally, assume that the plane of flow separation is a part of an ellipse, its origin (*O*), major radius (*L*), and minor radius (*W*). From Fig. 1:

$$\frac{X^2}{a^2}+\frac{Y^2}{b^2}=1 \qquad (1)$$

The boundary conditions:

First: at X=0, we find Y=W, by substituting in Eq. 1, we find:

b = +/- W (2a)

Second: at X=L, we find Y=0. By substituting in Eq.1, we find:

a = +/- L
(2b)

By substituting from (2a) and (2b) in (1) we get:

$$\frac{X^2}{L^2}+\frac{Y^2}{W^2}=1$$
(3)

Where *L* is the length of flow separation, and *W* is the maximum width of dead zone flow. Equation (3) is an equation of ellipse with major axis *(2L)*, and minor axis *(2W)*. The dead zone area of flow is considered equal to fourth the area of the ellipse, as shown in Fig. 1.

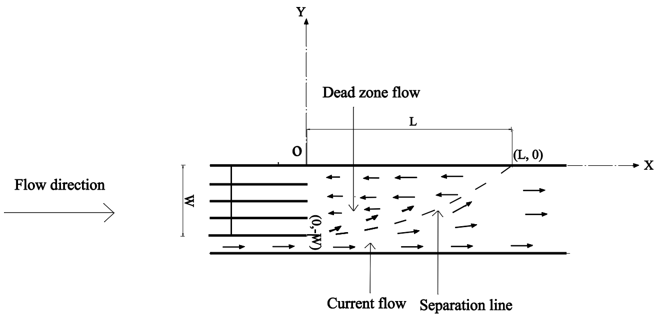


Fig 1. Definition sketch of separation line at any water plane.

II. Dimensional analysis

A physical pertinent relation between the length of flow separation (*L*) and the other dependent parameters may be found by dimensional analysis. From Fig. 2, the functional relationship of the length of flow separation (*L*) may be expressed by:

$$f\left(L,W,V,B,b_t,H_U,Y_3,Z,Y,G,Y_t,\rho,\mu\right)=0$$
(4)

Where:
L is the length of flow separation, *W* is the maximum width of dead zone flow, *V* is the mean velocity, ρ is the water density, *B* is the width of the channel, b_t is the width of the opened vents, *Z* is the depth of water plane from water surface, *Y* is the depth of water through the length of flow separation, *G* is the gate opening, H_U is the upstream water depth, Y_3 is the back up water depth, Y_t is the tail water depth, and μ is the dynamic viscosity of water.

Using $\prod$-theorem and considering $\rho, V,$ and *G* as the independent variables and by neglecting the effect of R_n (Reynolds number) and the relative tail water depth $\frac{Y_t}{G}$ (constant value=5), Eq. (4) takes the following form:

$$\frac{W}{L}=f\left(\frac{H_U}{G},e,\frac{Y_t}{Y_3},\frac{Z}{Y}\right) \qquad (5)$$

Where: *e* is the expansion ratio ($e=B/b_t$)

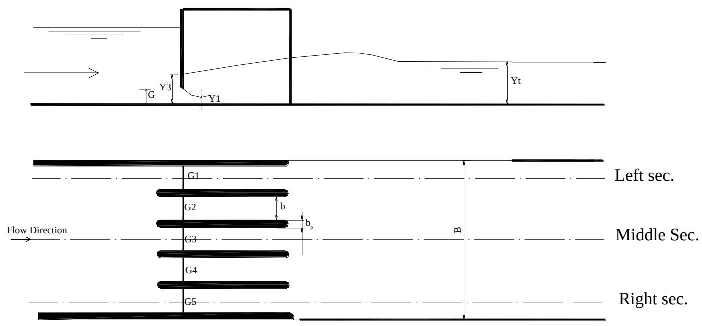


Fig 2. Definition sketch of Barrage's Mode.

Experimental Setup

The experimental work of the present research was carried out in the Hydraulic Research Institute (HRI), National Water Research Center (NWRC), Ministry of Water Resources and Irrigation (MWRI), Delta Barrages, Egypt. The dimensions of the flume used are 175cm wide, 42cm deep, and15m long, and is fabricated of wood with glass sides. The middle part consists of five rows of vents, each one 25cm wide, 38 cm deep and 85cm long. The width of pier is 10cm while the wing wall width is 5cm. The control sluice gates are made of wood (pezaform) and used to control the water depth through openings. The gates are at the upstream side of a sudden expanding stilling basin.

The discharge values are measured using ultrasonic flow-meter [type 1010 p/wp, and accuracy (+/-) 1%]. The operating scheme includes studying the openings of five, four, three, two and one side vent consecutively with variable expansion ratio $e=(B/b_t)$. Discharge flows vary from 10 to 40 l/s, the upstream water depths vary from 16 to 40 cm. The gate openings change from 2 to 5cm. The tail water depth varies from 7 to 21 cm. The discharge was adjusted to the desired value and the gate was opened to the chosen opening for the required flow conditions. Flow attained steady state condition after 15 minutes, the velocity vector (cm/s) downstream of the pier was measured by an Electromagnetic current-meter [sensor ellipsoid 11*33 mm with 10mm rod diameter, and accuracy (+/-)1%] through a mesh of points in the plan at the middle of each vent at 5cm, 40cm, 80cm, 150cm, 250cm, 350cm, 500cm, 950cm, and 1150cm from the piers until the end of dead zone flow, and for every point the velocity vector was measured at three different relative depths (Z/Y=0.2, 0.5, and 0.80). The end of length of flow separation (L) was also measured where the value of forward flow equal to nearly zero beside the left side wall.

ANALYSIS AND DISCUSSIONS

I- Effect of (H_U/ G), (Y_t/Y_3), and (e)

The variation of the dimensionless length of flow separation (*W/L*) compared to the relative gate opening (H_u/G), and the relative tail water depth (Y_t/Y_3) for different values of expansion ratio *(e)* is presented respectively through Fig. 3 and Fig. 4. These figures indicated that while (H_U/G), and (Y_t/Y_3) increases, the dimensionless length of flow separation (*W/L*) increases slightly, for different values of expansion ratios. While at high values of expansion ratio, higher values of *(W/L)* are attained. This can be interpreted as the number of closed vents increases, the flow passes through a limited width of channel, and the maximum width of dead zone flow *(W)* increases comparing to the length of flow separation *(L)*, and consequently the dimensionless length of flow separation (*W/L*) increases by increasing the expansion ratio (*e*).

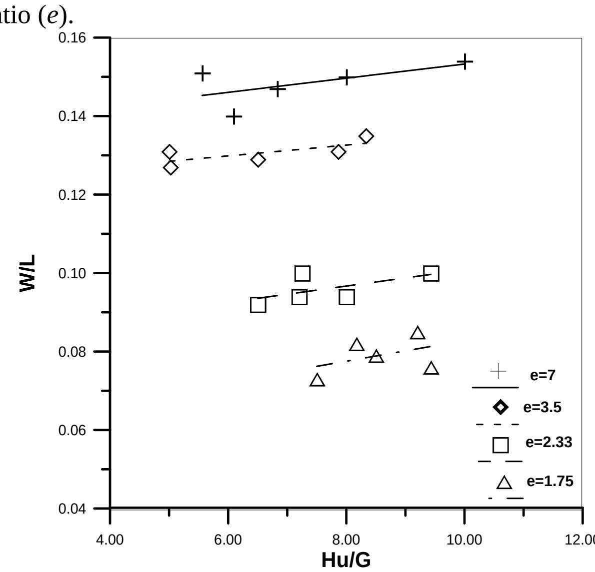


Fig 3. Variation of (W/L) against (Hu/G), for different (e) and (Y_t/Y_3=1-2).

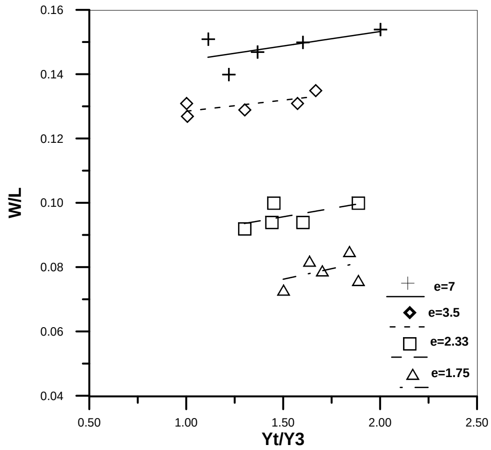


Fig 4. Variation of (W/L) against (Yt/Y3), for different (e) and (Hu/G=5-10).

Table 1 shows the summary of (*W/L*) values under different values of (*e*), and (*Hu/G*). The dimensionless length of flow separation (*W/L*) increases slightly by increasing (*Hu/G*) from 6 to 10, for different values of (*e*). Also, the dimensionless length of flow separation (*W/L*) increases noticeably with the increase of (*e*) from 1.75 to 7, for different values of (*Hu/G*).

Table 1. Summary of (*W/L*) values, for various (e) and (*Hu/G*)

	e=7	***e=3.5***	***e=2.33***	***e=1.75***
Hu/G =6	0.146	0.128	0.092	0.072
Hu/G =8	0.150	0.132	0.095	0.076
Hu/G =10	0.153	0.135	0.101	0.801

Table 2 shows the summary of (*W/L*) values for various (*e*), and (Y_t/Y_3). The dimensionless length of flow separation (*W/L*) increases slightly by increasing (Y_t/Y_3) from 1 to 2, for different values of (*e*). Also, the dimensionless length of flow separation (*W/L*) increases noticeably by increasing (*e*) from 1.75 to 7, for different values of (Y_t/Y_3).

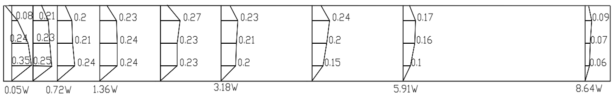
Table 2. Summary of (*W/L*) values, for various (e) and (Y_t/Y_3)

	e=7	***e=3.5***	***e=2.33***	***e=1.75***
Yt/Y3 =1.0	0.143	0.128	0.092	0.072
Yt/Y3 =1.5	0.140	0.132	0.095	0.075
Yt/Y3 =2.0	0.150	0.135	0.110	0.080

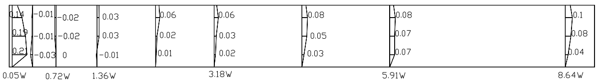
II Effect of flow separation on vertical distribution of component velocity (V_X)

Figs 5a, b, and c shows the vertical distribution of the velocity component (V_X) at longitudinal sections in the right, the middle, and the left of the channel, when two right side gates were opened (*e*=3.50). The velocity distribution at the right of the channel is positive because of the current flow effect. The velocity increases close to the surface of channel for a long distance ($X=5.91W$), as reported in **[10].**

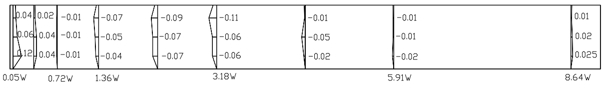
The velocity distribution at the left of the channel is negative up to a long distance ($X=5.91W$) because of the effect of flow separation, then it becomes positive because the end of flow separation and the regularity of flow. The negative values of the velocity at the middle and the left of the channel due to the effect of dead zone flow. The flow passes through a limited width of channel due to the effect of dead zone flow which extends to a long distance (*X=5.91W*), then the velocity was accelerated. So, the velocity profile in vertical direction is changed.



a) Right of channel.



b) middle of channel.

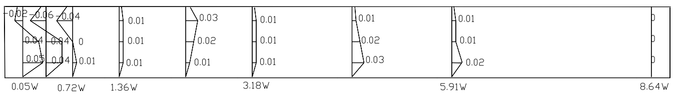


c) left of channel.

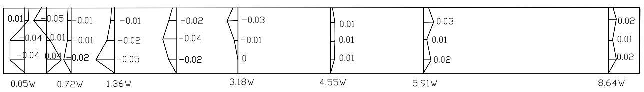
Fig 5. Vertical distribution of velocity (Vx) at longitudinal sections of model for (e=3.5).

III *Effect of flow separation on vertical distribution of component velocity (V_Y)*

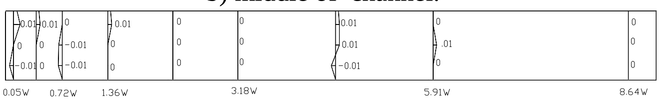
Figs 6 a, b, and c show the vertical distribution of the velocity component (V_Y) at longitudinal sections in the right, middle, and left of the channel, when two right side gates were opened (*e=3.50*). At the right of channel, most of values of (V_Y) are positive, because the effect of current flow and the slightly deflection towards the other side of the flume. At the middle of the channel, utmost values of (V_Y) are negative to a distance (4.55*W*) due to the effect of flow separation. After that the values of (V_Y) turn positive, because the end of flow separation and the regularity of flow. At the left of the channel, the common values of (V_Y) are equal zero, as the reverse flow collides and turns parallel to the side of the flume towards the multi-vent regulator.



a) Right of channel.



b) middle of channel.



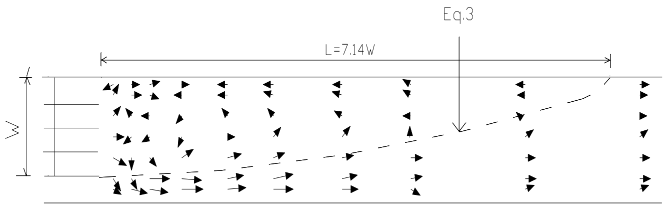
c) left of channel.

Fig 6. Vertical distribution of velocity (Vy) at longitudinal sections of model for (e=3.5).

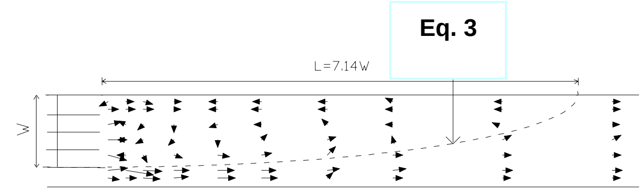
IV *Plane of separation*

The velocity vectors downstream of multi-vent regulator at depths 0.2*Y*, 0.5*Y*, and 0.8*Y* when one side vent was opened (*e*=7.00) are shown in Fig. 7. The flow is asymmetric and the main flow is divided into current flow and dead zone flow. There is a noticeable separation between the current and dead zone flows. Equation (3) presents the separation line as a part of ellipse, and shows better description for the separation line between current flow and dead zone flow (reverse flow and weak forward flow), which coincides with Ref. [9].

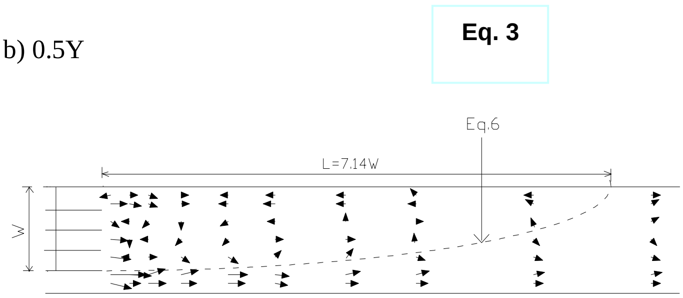
The length of the flow separation zone, and the area of dead zone flow seems to be nearly the same at different planes (0.2*Y*, 0.5*Y*, and 0.8*Y*), consequently the plane of separation can be considered vertical from the water surface to the channel bed.



a) 0.2Y



b) 0.5Y



c) 0.8Y

Fig.7 Distribution of velocity vectors for e=7, Hu/G=6.09, and Yt/Y3=1.35 at different planes.

The velocity vectors of the flow downstream multi-vent regulator for different relative upstream water depth and relative tail water depth (Y_t/Y_3=1.25-1.56) at water depth 0.5*Y* when one side vent was opened (*e=7*) are presented in Figs 8a and 8b. As previously stated, there is a noticeable separation between the current and dead zone flows. Equation (3) fit better the separation line between current flow and dead zone flow (reverse flow and weak forward flow), which coincides with Ref. [9]. The length of flow separation (L) decreases slightly as the relative upstream water depth increases. So, the dimensionless length of flow separation (W/L) increases slightly by increasing the relative upstream water depth (H_u/G).

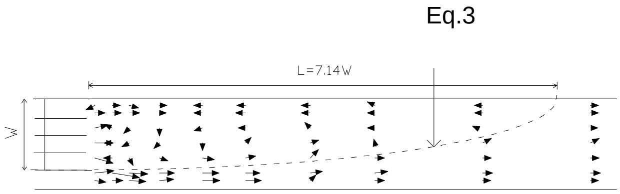


Fig.8a Distribution of velocity vectors for e=7, Hu/G=6.09, and Yt/Y3=(1.35-1.56) at 0.5Y.

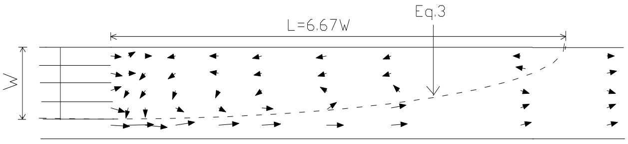


Fig.8b Distribution of velocity vectors for e=7, Hu/G=8, and Yt/Y3=(1.35-1.56) at 0.5Y.

The velocity vectors of the flow downstream multi-vent regulator for different relative tail water depth and relative upstream water depth ($H_u/G=5$) at water depth *0.5Y* when one side vent was opened ($e=7$) are presented in Figs 9a & 9b. The separation between the current and dead zone flows by equation (3) fit better the separation line, which agrees with Ref. [9]. The length of flow separation (L) decreases slightly as the relative tail water depth increases. So, the dimensionless length of flow separation (W/L) increases slightly by increasing the relative tail water depth (Y_t/Y_3). Figs 10a &10b show the velocity vectors of the flow downstream of multi-vent regulator for different expansion ratios (e) when relative upstream water depth (H_u/G = 8.00 - 8.50) and relative tail water depth ($Y_t//Y_3$=1.35-1.56) at depth 0.5Y, and equation (6) represents the separation line accurately, which coincides with Ref. [9]. As the number of closed vents increases, the flow passes through a limited width of channel, and the maximum width of dead zone *(W)* increases comparing to the length of flow separation *(L)*, and consequently the dimensionless length of separation (W/L) increases by increasing the expansion ratio (e).

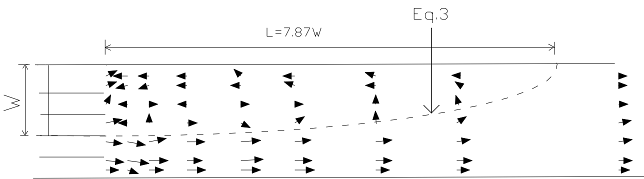


Fig. 9a Distribution of velocity vectors for e=3.5, Hu/G=5.00, and Yt/Y3=1.40 at 0.5Y.

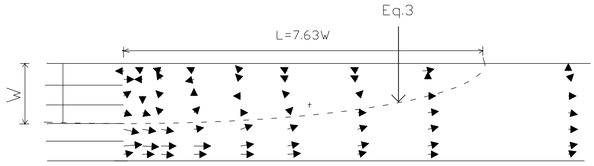


Fig. 9b Distribution of velocity vectors for e=3.5, Hu/G=5.00, and Yt/Y3=2.31 at 0.5Y.

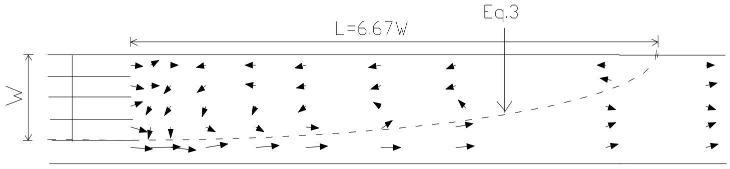


Fig.10a Distribution of velocity vectors for e=7, Hu/G=(8.00-8.50), and Yt/Y3=(1.35-1.56) at 0.5Y.

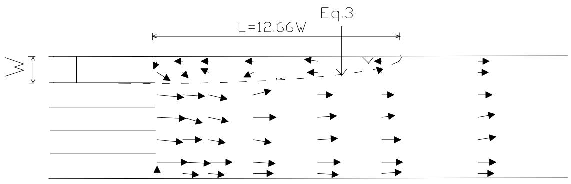


Fig.10b Distribution of velocity vectors for e=1.75, Hu/G=(8.00-8.50), and Yt/Y3=(1.35-1.56)at 0.5Y.

Prediction of (W/L)

Nonlinear and linear multiple regression analyses are used to correlate the different dimensionless parameters of equation (5), to develop empirical equation for computing the dimensionless length of flow separation (W/L). A general model was proposed and its coefficients were estimated, and can be written in the following:

$$W/L = \left(0.000892\frac{H_U}{G} - \frac{0.173}{e} + 0.00186\frac{Y_t}{Y_3} - 0.00071\frac{Z}{Y} + 0.166\right)$$

(6)

Fig. 11 shows the effect of each parameter on equation (6), and it is clearly that (Y_t/Y_3), (H_u/G), and (Z/Y) do not have a weight on this equation, and (e) has the greatest weight. So, the equation can be written in the following form:

$$W/L = \left(0.174 - \frac{0.17}{e}\right) \qquad (7)$$

(R^2 =96.15 %, S.E.E=0.0055)

From the previous formula, it is concluded that the dimensionless length of flow separation (W/L) does not exceed (0.174). So, the length of separation (L) does not be less than nearly six times the maximum width of flow separation zone (W). The protection length of canal sides and the distance of flow measurement downstream hydraulic structures must not be less than nearly six times the maximum width of flow separation zone (W) to avoid the

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effect of dead zone flow, and can be calculated accurately by equation (7).

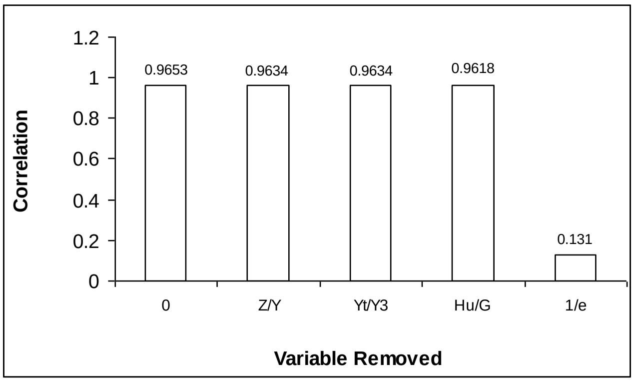

Fig.11 The Relationship between variable removed from Eq. (6) and correlation.

CONCLUSIONS

In this study the assumption of the separation zone between current flow and dead zone flow (reverse flow and weak forward flow) as a part of ellipse is particularly verified by plotting velocity vectors at different sections. It is found that dimensionless length of flow separation *(W/L)* remains constant when the relative depths of water plane *(Z/Y)* changed, under different values of relative upstream water depth *(Hu/G)*, and relative tail water depths (Y_t/Y_3), for the same expansion ratio *(e)*. While the dimensionless length of flow separation *(W/L)* increases slightly with the increase of the relative upstream water depth *(Hu/G)*, and the relative tail water depth *(Yt/Y3)*, for different values of expansion ratio *(e)*.Values of (*W/L*) are mainly affected by the expansion ratio *(e)*. At higher values of *(e)* higher *(W/L)* are found for different relative tailwater depths (Y_t/Y_3), relative depths of water plane *(Z/Y)*, and relative upstream water depth *(Hu/G)*.The importance of this research is in developing Statistical model based on the multiple linear regressions, to predict the dimensionless length of flow separation, when side gates are operated. It proved that, the dimensionless length of flow separation (*W/L*) does not exceed (0.174). So, the length of flow separation (*L*) does not decrease than nearly six times the maximum width of flow separation zone (*W*). So as a main finding of this work, equation (10) was deduced empirically and verified physically to show that the protection length of canal sides and the distance of flow measurement downstream hydraulic structures can be calculated accurately.

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