IMPROVING THE PIPE CULVERT EFFICIENCY BY USING INCLINED HEADWALLS

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ABSTRACT

The inlet and exit geometry of the pipe or circular culverts has a significant importance in improving its performance, and increasing its efficiency. That is why the present experimental study focuses on testing the influence of equipping an inclined headwall in such culverts on the hydraulic efficiency, and comparing the results with the projected culvert (culvert without headwall). The present research consists of three trends of experiments, the first one for testing the effect of equipping an inclined headwall in the U.S. side of the circular culvert, while the second trend for testing the effect of equipping an inclined headwall in the D.S. side of the circular culvert, and the third trend was for testing the effect of equipping an inclined headwall in both sides of the circular culvert (U.S. and D.S.). In each trend, there are five models of headwall with variable inclination angle ranging from 15° to 90° were used in addition to the projected one as a reference for comparison purposes with a total of 240 runs. The study introduced a new effective tool for improving the circular culvert efficiency and insuring more safety for the traffic over such roads. The study showed that, the headwall of inclination angle 15° in the opposite direction of the flow gives the best results and the maximum discharge efficiency under the same upstream water depth in case of using U.S. headwall only, while for using the headwalls in both sides of the circular culvert, the inclination angle of 60° is the best one. But, using the headwall in the D.S. side only has a negative impact on the hydraulic efficiency of the circular culvert.

Keywords: Circular culvert efficiency, Inclined headwall, Outlet control, Culvert geometry.

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1 INTRODUCTION

The aim of the present study is introducing an efficient way to protect the pipe culvert against the expected attack of the flash flooding or torrents by improving their hydraulic efficiency. After reviewing the available previous research concerning the topic of the present study, and discussing their main results and conclusions, the following main technical points can be highlighted:

- Using the beveled or the rounded edge barrels improves the hydraulic efficiency of culverts compared with the sharp-edged barrels (Lorenz et al., 1953).
- The performance of culverts is significantly affected by the shape of the entrance and configurations (Khalil and Zein, 1995).
- Using the vertical headwall at the upstream side improves the hydraulic efficiency, and maintains the same discharge with low water height at the upstream side (Smith and Oak, 1995).
- For the circular pipe culvert, the best inlet shape is the tapered inlet with slope 4:1, which gives the minimum head loss for the outlet control (Khaled, 2004).
- Using an inclined headwall of inclination angle 15° in the opposite direction of the flow in the U.S. side, gives the best hydraulic efficiency for circular culvert compared with the projected one, which is the worst shape of the culvert inlet (Ashour et al., 2016).
- The best inclination angle for using the inclined headwall in both sides of the box culvert is 30° in the opposite direction of the stream flow, which enhanced the head loss with an average value 16% with respect to the projected culvert (Aly and Ashour, 2017).

From the presented literature review, It is clear that, there are many tools for enhancing the discharge efficiency of the culverts such as using rounded inlets, beveled-edge inlets, side or slope tapered inlets (James et al., 2012; Normann, 1975; Harrison et al., 1972), but there is no attempt for studying the effect of using inclined headwall as a tool for improving the desert-road culvert performance. Only Ashour et al. (2016) investigated the effect of using an inclined headwall on the hydraulic efficiency of the circular culvert and box culvert, only for the case of the U.S. side of the culvert. Aly and Ashour (2017) studied the effect of using inclined headwalls in both sides of culvert but only for the box culvert. So, in this work a study was carried out to test the influence of equipping a headwall with different inclination angles in the U.S. side, in the D.S. side and in both sides of the circular culvert, and comparing the results with the corresponding ones for the case of projected culvert.

2 THEORETICAL APPROACH

Culverts can operate with inlet or outlet control depending on the location of the control section, which is affecting on the hydraulic efficiency of the culvert (Normann et al., 1985). Inlet control condition depends on the U.S. water depth, inlet geometry, shape of the culvert barrel and edge configuration, while the outlet control condition depends on all factors may affect the flow, such as U.S. and D.S. water depth, barrel shape, slope, length and barrel roughness. In case of inlet control, the culvert behaves as an orifice, where the culvert barrel is running partially full while the U.S. is submerged and in case of outlet control, the culvert barrel is running full and the culvert is acting as a pipe flow, as shown in figure (1).

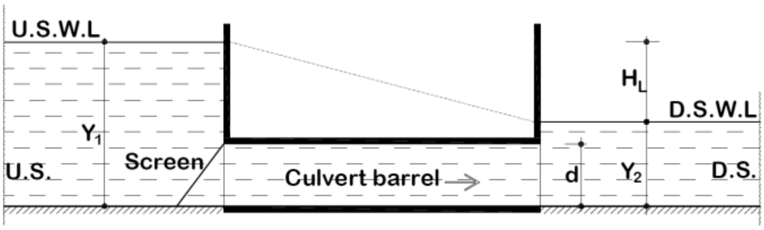


Figure1. A culvert operates with outlet control conditions

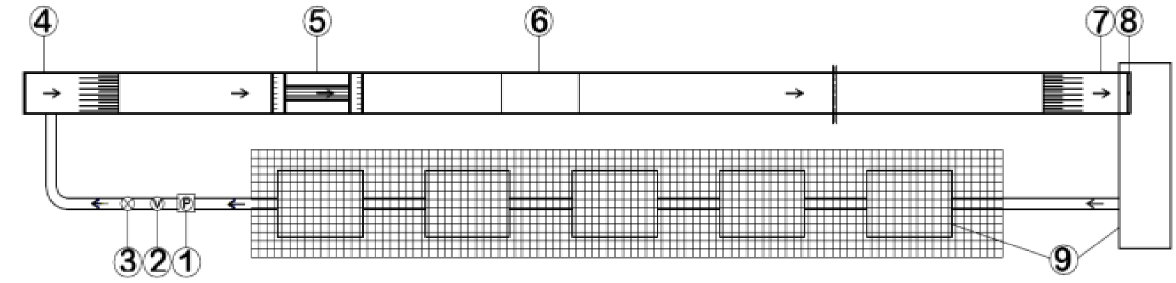
The present study focuses on the effect of the inclined headwall equipped in the U.S. and D.S. sides of circular culvert on the hydraulic efficiency. So, all the experiments of the present study were carried out in case of outlet control condition and the relationship between the head loss and the discharge can be written as follows:

$$H_L = K\frac{Q^2}{2gA^2} = \left[K_{in} + K_{sc} + K_{fr} + K_{ex}\right]\frac{V^2}{2g} \quad (1)$$

Where the headwall type affects on the value of the inlet and the exit loss coefficients, (K_{in} and K_{ex}).

3 EXPERIMENTAL SET-UP

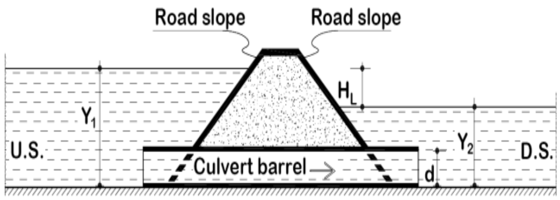
Experiments were carried out in a re-circulation rectangular open channel in the Irrigation and Hydraulic Laboratory at Assiut University, as shown in figure (2). The channel is 20 m long, 30 cm wide and 50 cm depth, with an adjustable slope. A tail gate is located at the end of the channel to control the downstream water depth. The discharge is delivered by a pump and measured using a calibrated orifice meter. The U.S. and D.S. water depths (Y_1 and Y_2), are measured using an electrical point gauge.



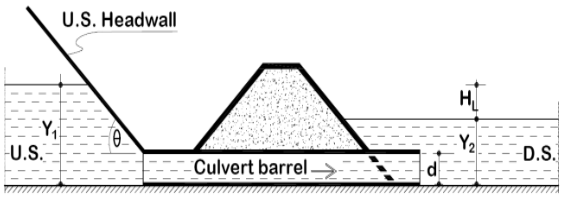
(1) PUMP
(2) VALVE
(3) ORIFICE METER
(4) APPROACH BASIN
(5) CULVERT MODEL
(6) WAVE CALMING PLATE
(7) DOWNSTREAM RAMP
(8) TAILGATE
(9) COLLECTING TANKS

Figure 2. Experimental Set-Up.

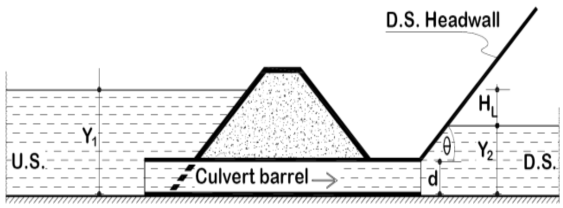
A UPVC pipe of an inner diameter (d) equals 10.16 cm and 100 cm length was used for testing the circular culvert barrel as shown in figure (3).



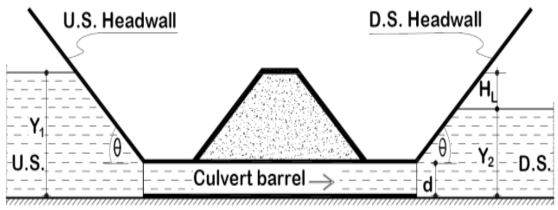
(a) Projected culvert model (culvert without headwall) for comparison purposes



(b) The model used for testing the effect of headwall inclination in the U.S. side of the circular culvert



(c)The model used for testing the effect of headwall inclination in the D.S. side of the circular culvert



(d)The model used for testing the effect of headwall inclination in both sides of the circular culvert.

Figure 3. Types of tested headwall models

4 EXPERIMENTAL APPROACH

To recommend the most efficient inclination angle of the headwall which permits a passage of minimum head loss, the experiments were divided into three pivots, the first one for determining the effect of equipping a headwall with an inclination angle (θ) in the U.S. side of the pipe culvert, the second pivot for determining the effect of equipping a headwall with an inclination angle (θ) in the D.S. side of the pipe culvert and the third for determining the effect of equipping a headwall with an inclination angle (θ) in both sides of the culvert. The types of the tested headwall models are shown in photo (1).

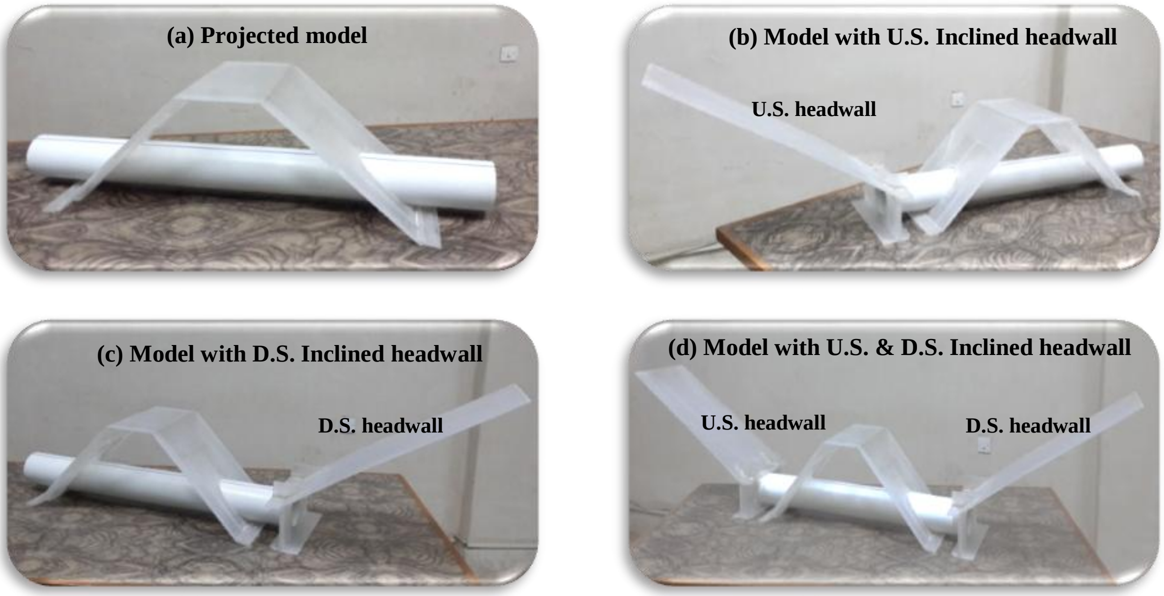


Photo 1. Types of used experimental models.

In each trend, there are five models of headwalls with variable inclination angle (θ) were used where (θ) = 15°, 30°, 45°, 60° and 90° in addition to the projected one as a reference for comparison purposes. Five discharge values were used with each model ranging from 7.97 to 13.52 L/s to reach velocities ranging from 0.98 to 1.67 m/s, and three values for relative submersion values (Y_2/d) were used, ranging from 1.75 to 2.25. So, 15 runs were carried out for each model with a total number equals 240 runs. Photo (2) shows the D.S. inclined headwall during the experiment.

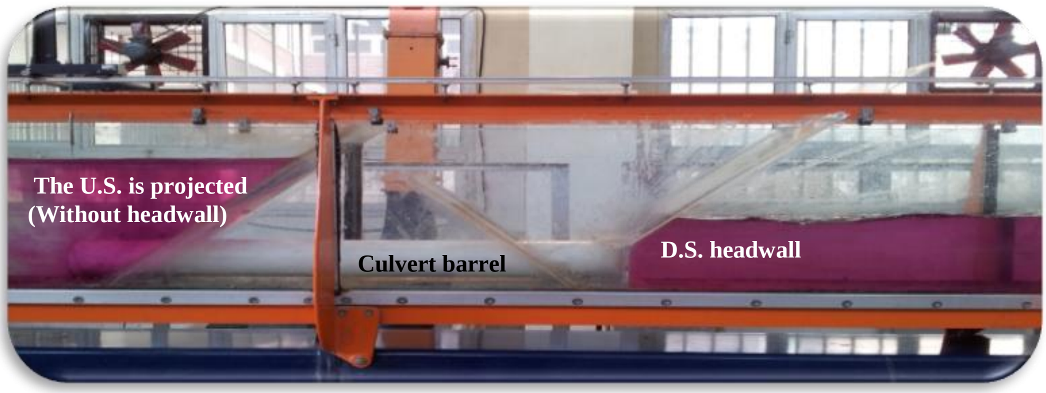


Photo 2. Testing the effect of D.S. inclined headwall

5 ANALYSIS AND DISCUSSION

All headwalls were prepared to be tested for determining the head loss in case of the submerged outlet control condition and the obtained results were compared with the projected culvert. The experiments were carried out in three trends as follows:

1) Testing the effect of equipping an inclined headwall in the U.S. side of the circular culvert;
2) Testing the effect of equipping an inclined headwall in the D.S. side of the circular culvert;
3) Testing the effect of equipping an inclined headwall in both sides of the circular culvert.

5.1 Effect of an Inclined Headwall in the U.S. Side

In this trend, five models of headwall of an inclination angle (θ) equals 15°, 30°, 45°, 60° and 90° were equipped at the barrel entrance of the circular culvert, in addition to the projected one as a reference. The relation between the head loss (H_L) and the headwall inclination angle (θ) in case of a relative submersion value (Y_2/d) equals 1.75, is shown in figure (4).

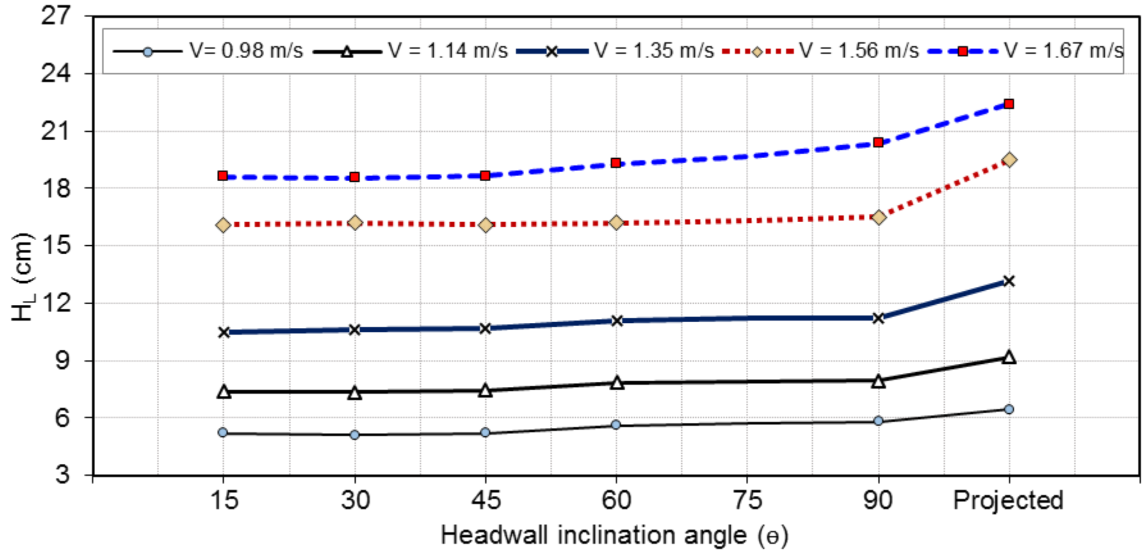
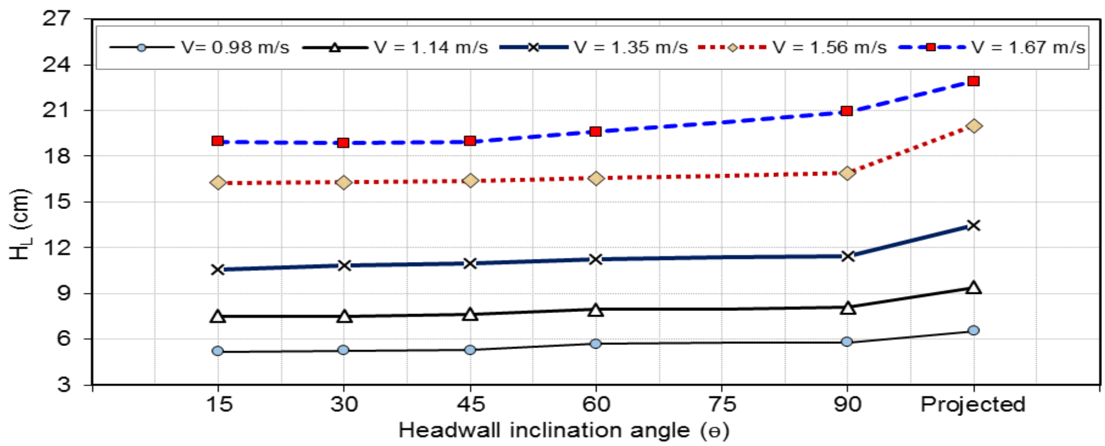


Figure 4. The relation between the head loss and the headwall inclination angle (using U.S. headwall & Y_2/d =1.75)

From which it can be noticed that, the best inclination angle for a headwall used in the U.S. of the circular culvert is 15°, where the head loss decreases with the decrease of the headwall inclination angle till it reaches 15°, which agrees with Ashour et al. (2016). The same relation was plotted for a relative submersion value (Y_2/d) equals 2.0 and 2.25 as shown in figures (5) and (6) respectively, from which it could be proved clearly that, using 15° inclined headwall in the U.S. side of the circular culvert enhanced the hydraulic efficiency of the circular culvert in case of relative submersion values (Y_2/d) equal 1.75, 2.0 and 2.25 with 18.7%, 19.6 and 20.1 respectively, with respect to the projected culvert, which means that, it is very important using a headwall in the U.S. side of the circular culvert which reduces the head loss with an average value equals 13 % in case of vertical headwall till it reaches 19.5 % in case of a headwall of an inclination angle equals 15°, for the used submersions ratios ranging between 1.75 to 2.25.



Figuer 5. The relation between the head loss and the headwall inclination angle (using U.S. headwall & Y_2/d =2.0)

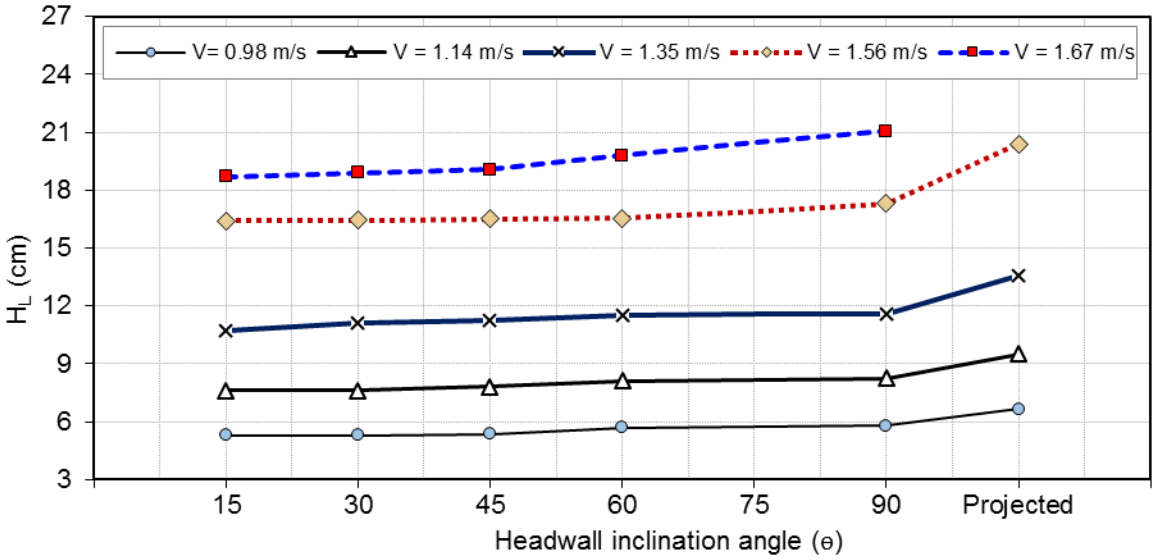


Figure 6. The relation between the head loss and the headwall inclination angle (using U.S. headwall & Y_2/D =2.25)

Table (1) shows the effect of headwall of an inclination angle 15°, equipped in the U.S. side of the circular culvert model on the inlet and the exit losses coefficient, (K_{in} + K_{ex}).

Table (1). Values of the inlet and exit losses coefficients (K_{in} +K_{ex}) for the projected culvert model and 15° headwall model equipped in the U.S. side of the pipe culvert

Relative submersion value (Y_2/d)	**1.75**		**2**		**2.25**		**Average**	
Headwall model	**Projected**	**15°**	**Projected**	**15°**	**Projected**	**15°**	**Projected**	**15°**
(K_{in} +K_{ex})	**1.34**	**1.07**	**1.37**	**1.08**	**1.38**	**1.09**	**1.36**	**1.08**

From the table, it can be noticed that, for the range of the used velocities (from 0.98 to 1.67 m/s), and the range of the used relative submersion values (from 1.75 to 2.25), using a headwall of an inclination angle 15° decreases the values of (K_{in} + K_{ex}) from 1.36, in case projected model, to 1.08, with an average value equals 20.5%.

5.2 Effect of an Inclined Headwall in the D.S. Side

In this trend of experiments, five models of headwall of an inclination angle (θ) equals 15°, 30°, 45°, 60° and 90° were equipped at the barrel exit (D.S. side) of the circular culvert, in addition to the projected one as a reference. The relation between the head loss (H_L) and the headwall inclination angle (θ) in case of a relative submersion value (Y_2/d) equals 1.75, is shown in figure (7), from which it can be noticed clearly the negative impact of using the inclined headwall in the D.S. side of the circular culvert on the hydraulic efficiency, especially with the small inclination angles.

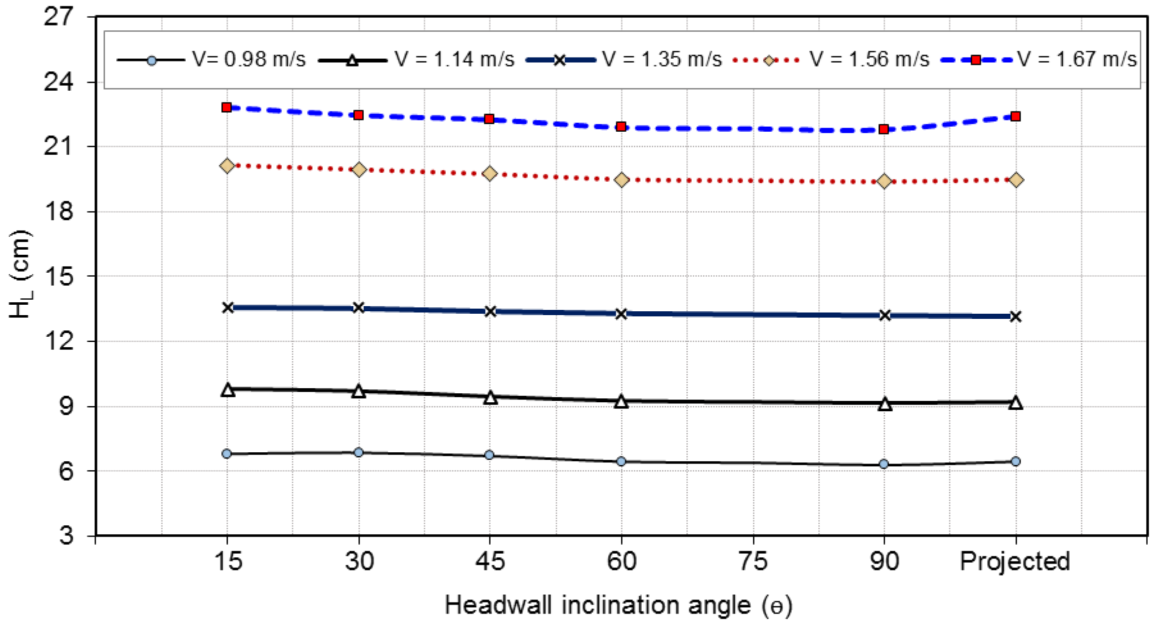


Figure 7. The relation between the head loss and the headwall inclination angle (using D.S. headwall & Y_2/d =1.75)

The same relation was plotted for a relative submersion value (Y_2/d) equals 2.0 and 2.25 as shown in figures (8) and (9) respectively, from which it could be proved that, using a vertical headwall (θ = 90°) decreases the head loss with a very small value of about 2 %, and for smaller inclination angles, the effect reduces till it vanishes when the inclination angle reaches 60°, after that angle the effect changes to have a negative impact on the hydraulic efficiency, where the average increase in the head loss reaches about 3.5 % at inclination angle equals 15°.

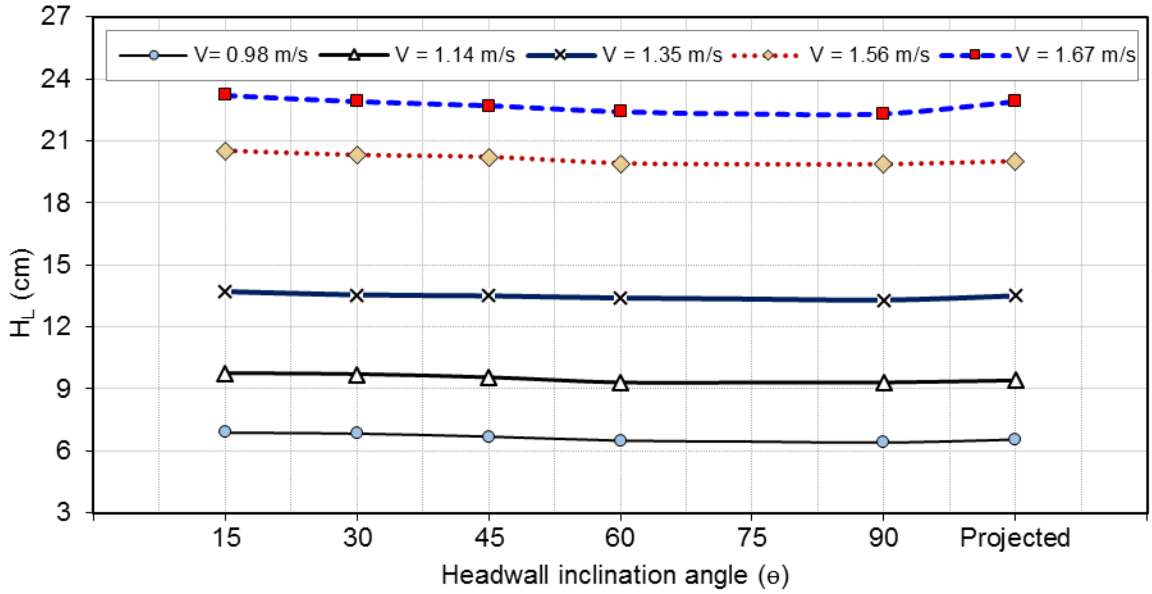


Figure 8. The relation between the head loss and the headwall inclination angle (using D.S. headwall & Y_2/d =2.0)

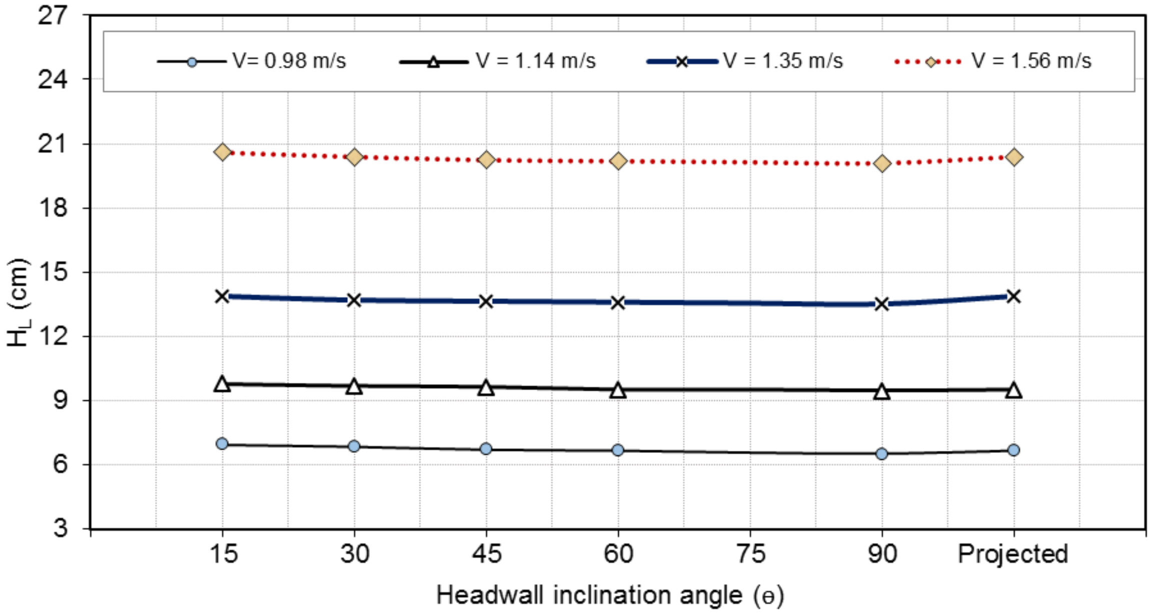


Figure 9. The relation between the head loss and the headwall inclination angle (using D.S. headwall & Y_2/d =2.25)

5.3 Effect of an Inclined Headwall in both Sides

Due to the possibility of the flow to change its direction through the culvert barrel, so in this case it is required to use the same inclined headwall in both sides of the culvert. In this trend, five models of headwall of an inclination angle (θ) equals 15°, 30°, 45°, 60° and 90° were equipped at the inlet and exit of the circular culvert, in addition to the projected model as a reference, to get the most efficient headwall inclination angle

Figure (10) shows the relation between the head loss (H_L) and the headwall inclination angle (θ) in case of a relative submersion value (Y_2/d) equals 1.75. The figure showed that, using inclined headwalls in both sides of the circular culvert increases the hydraulic efficiency of the circular culvert by decreasing the head loss, this enhancement in the efficiency increases with the decrease in the inclination angle of the headwall till it reaches 60° then the efficiency deceases again, which may be related to the negative effect of D.S. inclined headwall. Figures (11) and (12) clear this note for the used relative submersion values equal 2.0 and 2.25 respectively.

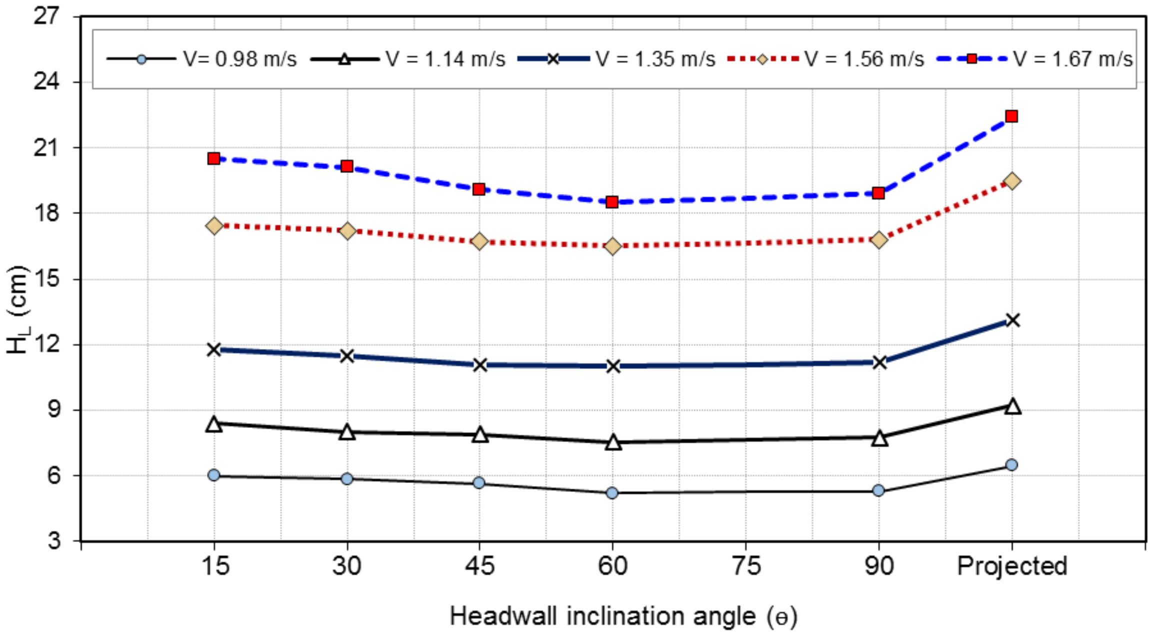


Figure 10. The relation between the head loss and the headwall inclination (using U.S. & D.S. headwall &Y_2 /d =1.75)

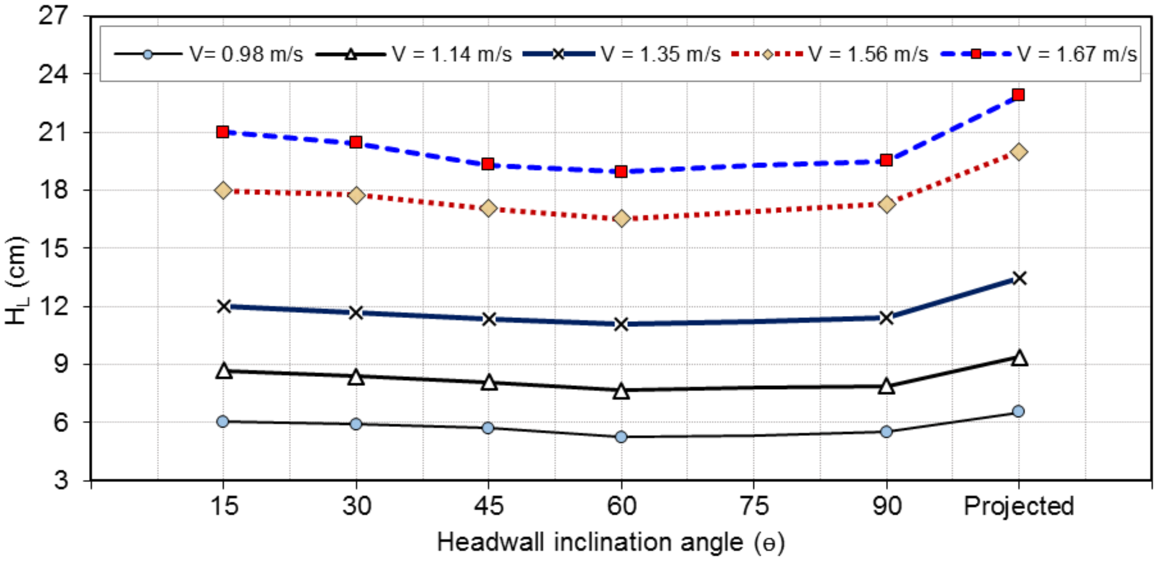


Figure 11. The relation between the head loss and the headwall inclination (using U.S. & D.S. headwall &Y_2/d =2.0)

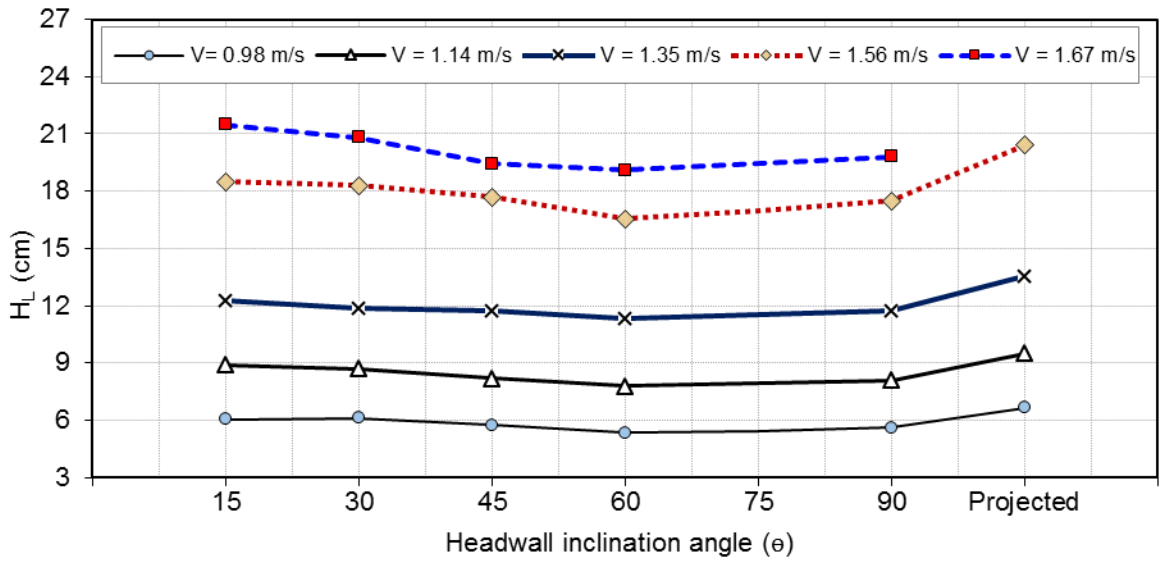


Figure 12. The relation between the head loss and the headwall inclination (using U.S. & D.S. headwall &Y_2/d =2.25)

Through figures (10) to (12), it can be concluded that, for the used relative submersion values ranging from 1.75 to 2.25, the maximum value of decreasing the head loss in case of using an inclined headwall in both sides of the circular culvert can be achieved at an inclination angle equals 60°, with a value equals 17.5 % with respect to the projected culvert.

Table (2) shows the effect of headwall of inclination angle 60° equipped in both sides of the circular culvert model on the inlet and the exit loss coefficients, (K_{in} + K_{ex}), from which it can be noticed that, for the range of the used velocities (from 0.98 to 1.67 m/s), and the range of the used relative submersion value (from 1.75 to 2.25), using a headwall of an inclination angle 60° in both sides of the circular culvert decreases the values of the inlet and the exit losses coefficient, (K_{in} + K_{ex}) from 1.36, in case projected model, to 1.11, with an average value 18.5%.

Table (2) Values of the inlet and exit loss coefficients (K_{in} +K_{ex}) for the projected culvert model and 60° headwall model equipped in both sides of the pipe culvert.

Relative submersion value (Y_2/d)	**1.75**		**2**		**2.25**		**Average**	
Headwall model	**Projected**	**60°**	**Projected**	**60°**	**Projected**	**60°**	**Projected**	**60°**
(K_{in} +K_{ex})	**1.34**	**1.09**	**1.37**	**1.11**	**1.38**	**1.14**	**1.36**	**1.11**

6 CONCLUSIONS

Through the experimental results and discussion, the following main technical points were concluded:

- The inclined headwall is an effective tool for improving the efficiency of the circular culverts.
- Using a headwall in the U.S. side of circular culvert, of an inclination angle 15° in the opposite direction of the stream flow gives better results than that obtained with other tested values of inclination angles, where it enhances the hydraulic efficiency of the circular culvert by decreasing the head loss with an average value of about 19.5 % and decreases the values of (K_{in} + K_{ex}), by about 20.5% with respect to the projected culvert.

- Using an inclined headwall with an inclination angle less than 60° in D.S. side of circular culvert has a negative impact on enhancing the hydraulic efficiency.
- Using a headwall in both sides of circular culvert, of an inclination angle of 60° in the opposite direction of the flow gives better results than that obtained with other tested inclination angles, where it decreases the head loss with an average value equals 17.5 %, and decreases the values of (K_{in} + K_{ex}) with an average value equals 18.5% with respect to the projected culvert.
- Using the vertical headwall (θ = 90°) in the U.S., D.S. and in both sides, enhances the hydraulic efficiency of the circular culvert with a value of about 12 %, 2 % and 15 % respectively.

NOTATIONS

The following symbols are used in this paper:

A : Culvert cross sectional area;
C_d : Discharge coefficient;
d : Diameter of circular culvert;
g : Gravitational acceleration;
H_L : Head loss;
h : U.S. water depth measured from the axis of the culvert;
K : Coefficient of head loss;
K_{ex} : Exit losses coefficient;
K_{fr} : Fiction losses coefficient;
K_{sc} : Screen losses coefficient;.
K_{in} : Inlet losses coefficient.
L : Length of the culvert;
Q : Discharge;
Y_1 : U.S. water depth measured from the bottom of the culvert; and
Y_2 : D.S. water depth measured from the bottom of the culvert.

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