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INCLINED HEADWALL IS AN EFFICIENT TOOL FOR MAXIMIZING THE DISCHARGE EFFICIENCY THROUGH CULVERTS

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ABSTRACT

Many authors and researchers examined and tested several methods and tools for improving the performance efficiency of the culverts. Owing to increase the importance of the desert roads nowadays for joining the new constructed industrial and agricultural communities all over Egypt, and because of the draught nature of that new desert areas, for which the desert road network was constructed, and the possibility of the harmful and destructive impact of the torrents and flash floods periodically occurs in such regions, our present work will be focusing on the under desert road culverts. The role of the under desert road culverts is the prime factor in the constructional, and traffic safety of such roads. Its efficiency in converting the accumulated flash water from one side of the road to the other side at a significantly very short time protects the roads against failure due to overlapping. The present work introduces a new constructional simple tool for maximizing the discharging efficiency of the under desert road culverts, and insuring its constructional safety in addition to the safety of the traffic over them. The introduced tool (as the best of our knowledge) wasn't investigated yet, or technically examined by any of the authors reviewed in the literature. 10 models of the inclined headwall with different inclination angles in the same direction of the stream flow, and in the opposite direction were tested. The optimum inclination angle which gives the maximum discharge under the minimum U.S. water head, for more safety of desert road against flash floods and torrents was introduced.

Keywords: Inclined Headwalls, Flash floods, Hydraulics of under desert road culverts.

1 INTRODUCTION

As it is well known, about one-third of the earth's land is arid to semiarid, in such regions, owing to thunderstorms sometimes occur and can produce heavy and intense rainfall that can cause flooding. Many factors determine the size of flooding, including; the rate of rainfall and its duration; how dry or wet the land is, topography, ground cover and many other factors. The scope of the current study is the desert extension of Upper Egypt Governorates in which many new agricultural and industrial communities were constructed during the two last decays, through Upper Egypt accelerating developing and improving programs. Great net of desert roads for joining such new communities with their mother cities, and other governors were aligned and constructed. As it is clear from the following photo, circular concrete culverts were the most popular engineering tool used for protecting such great desert road nets and highways against flash floods and torrents (see photo 1).

Photo 1. (a & b) Under desert road culverts carried out in the western Assiut City desert.

From the photos it is clearly noticed that the used protecting culverts were constructed without any engineering treatment for their entrances to enhance and improve their hydraulic performance to increase their discharging efficiency of converting any accumulated water of flash floods from one side of the road to the other side (as much as possible of water, at as short as possible time), to prevent the overtopping of the road and stopping its safely use in traffic, in addition to the destructive effect may the construction of the road can exposed. Along the last twenty years, more than once, the flash floods, and torrents attacked the main highways in the Eastern desert of the nearby areas of Assiut City, and El-Minia, [1] causing a huge damage to road body, and stopped the traffic stream joining many of the Upper Egypt Cities, and affecting negatively the commercial and daily human activities.

In the present study, we try to investigate some new engineering treatments for such culvert entrances, for achieving the most practicable geometrical configuration that ensures maximum hydraulic performance efficiency in converting any accumulated water from one side of the desert road to the other side, while the surface traffic over the road is running safely and in a normal condition. After studying carefully, and well surveying of the previous researches concerning the under study topic, we discovered that using the inclined headwalls in the entrance of such culverts wasn't tested or studied yet. So, ten angels of inclination to the stream flow (15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135° and 150°) in the same direction and in the opposite direction of the flow were tested, and its influence in the discharge efficiency was examined using two different types of culvers (circular and box).

All the 10 inclined headwall models were tested with each type of under study culverts having the same cross-sectional area. The obtained results for measured different hydraulic parameters were recorded, tabulated, plotted, and discussed carefully. A comparative study was carried out between the obtained results of the two tested culverts, and also with the results of other previous authors. The study introduced a new effective tool for improving the under desert road culverts and insuring more safety for the traffic over such roads. Also the study showed that the headwall of inclination angle 15° in the opposite direction of the flow gives the best results and the maximum discharging efficiency under the same upstream water depth.

2 THEORETICAL APPROACH

There are two conditions of flow through culverts, depending on the location of the control section, they can operate with inlet or outlet control because they have a great impact on the discharging efficiency of the culvert. Inlet control condition, in which the water can flow through and out of the culvert faster than it can enter, the culvert is called under inlet control, depends on the U.S. water depth, shape of the culvert barrel, inlet geometry and edge configuration, while the outlet control condition in which, the water can flow into the culvert faster than it can flow through and out, depends on all factors may affect the flow, such as U.S. and D.S. water depth, barrel shape, length, slope, and barrel roughness. In case of inlet control, the culvert barrel is running partially full while the U.S. is submerged. The capacity of the culvert is reduced due to the extracted area filled with air, and the culvert behaves as an orifice, see figure (1-a). The relationship between the discharge and the U.S. water depth in this case can be written as the following well known equation:

$$Q = C_d A \sqrt{2gh} \tag{1}$$

In case of outlet control, the culvert barrel is running full because of the effect of the barrel length and the D.S. water level. The culvert is acting as a pipe flow, where the flow is passing through the culvert by pressure and weight forces as shown in figure (1-b) for free outlet, and figure (1-c) for submerged outlet.

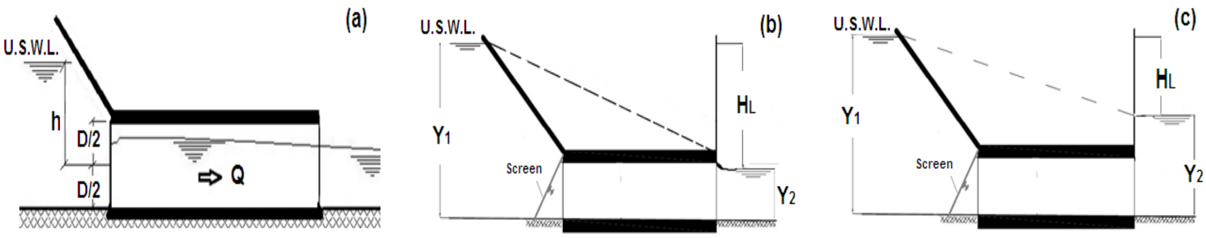


Figure 1. Conditions of flow for culverts.

The relationship between the head loss and the discharge can be written as follows:

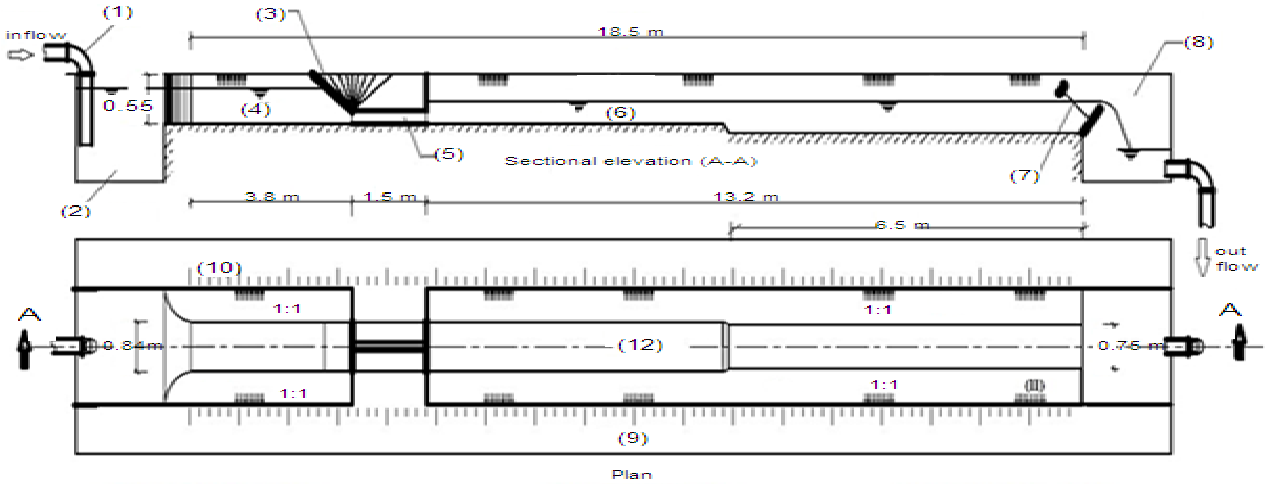
$$H_L = \left[K_{in} + K_{sc} + K_{fr} + K_{ex}\right]\frac{Q^2}{2gA^2} \tag{2}$$

$$H_L = K\frac{Q^2}{2gA^2} \tag{3}$$

$$K = \left[K_{in} + K_{sc} + K_{fr} + K_{ex}\right] \tag{4}$$

3 EXPERIMENTAL SETUP

In masonry channel of a trapezoidal cross sectional shape, 25 m. length, 0.84 m bottom width, 0.55 m height, and side slope 1:1 in the irrigation laboratory of the civil engineering Dept., Assiut university, equipped with all needed measuring devices. The tested headwalls with different inclination angles were fixed over the entrance of the two tested types of culverts which located individually one by one in the testing channel and examined under the available laboratory discharges ranging between 15 and 40 l/s, supplied from the laboratory closed system with a constant head as shown in figure (2).



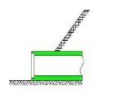
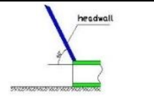
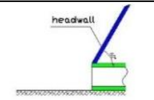
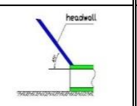
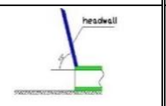
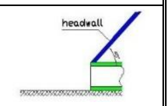
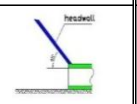
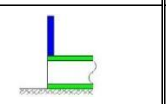
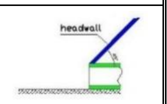
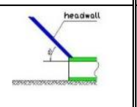
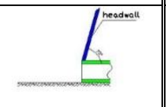
(1) Feeding pipe line
(2) Intake tank
(3) Headwall model
(4) U.S. part of the channel
(5) Culvert barrel
(6) D.S. part of channel
(7) Tailgate
(8) Outlet tank
(9) Channel foot path
(10) Horizontal scale
(11) Channel side slope
(12) Channel bed

Figure 2. Schematic diagram of the experimental facility.

4 EXPERIMENTAL PROGRAM

For knowing the influence of the presented new headwall angles of inclinations on the different hydraulic parameters affecting the discharge efficiency through under desert road culverts, two groups of experiments were carried out (one for the circular culvert, and the other for the box culvert). The 10 under study angles of inclination of the introduced headwall were erected individually over the entrance of the culvert of each type, and tested by measuring the needed hydraulic parameters with different values of discharge. The obtained results were recorded and presented in a group of tables and graphs, from which the needed equations joining the most effective hydraulic parameters with the discharge coefficient, head loss, and angle of inclination be obtained for the two tested types of culverts. The following table (1) gives the introduced tested new headwall, and the angles of its inclinations.

Table 1. Types of tested headwall models

Model No.	Inclination angle (θ)	Shape	Model No.	Inclination angle (θ)	Shape	Model No.	Inclination angle (θ)	Shape
1	Projected culvert		5	60°		9	120°	
2	15°		6	75°		10	135°	
3	30°		7	90°		11	150°	
4	45°		8	105°				

5 ANALYSIS AND DISCUTION

The experiments mentioned, and described above were carried out twice for each type of tested culverts, one for the inlet control condition, and the second for the outlet control condition. In all cases the obtained results were compared with that obtained with the projected culvert (the culvert without any head walls).

5.1 Results of circular culvert model

5.1.1. The effect of headwall inclination angle on the discharge coefficient (case of inlet control)

Figure (3) shows the relationship between the discharge (Q) and the U.S. water depth (h) for different angles of inclination, from which it can be noticed that:

- Using the tested headwalls increases the performance efficiency of the circular culvert.
- Culvert models with headwalls incline in the opposite direction of the flow give better results than those with headwalls incline in the direction of the flow.
- The best angle of inclination that gives the lower water depth at the U.S. for the same discharge value is angle 15° in the opposite direction of the flow.
- The projected inlet changes the flow direction with 180° but using the inclined headwalls in the direction of the flow decreases this change until the angel reaches 15° that is why the 15° headwall is the best.

Figure (3) shows the effect of the headwall angles of inclination on the discharge coefficient.

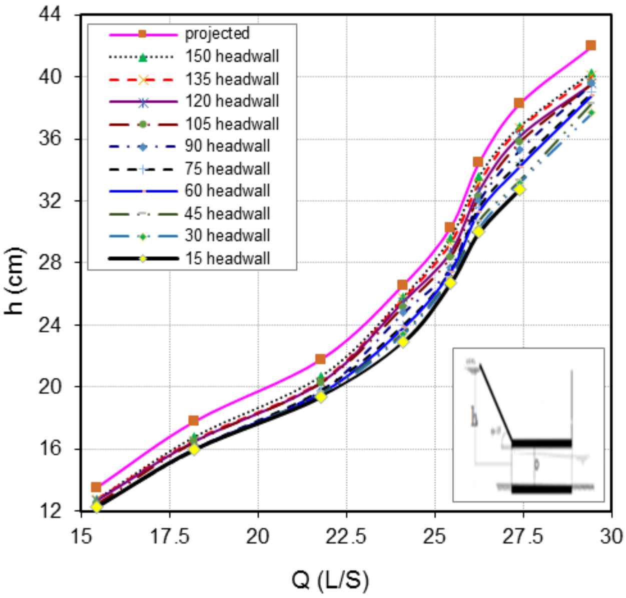


Figure 3. Relationship between the discharge and the U.S. water depth for circular culvert models (case of inlet control).

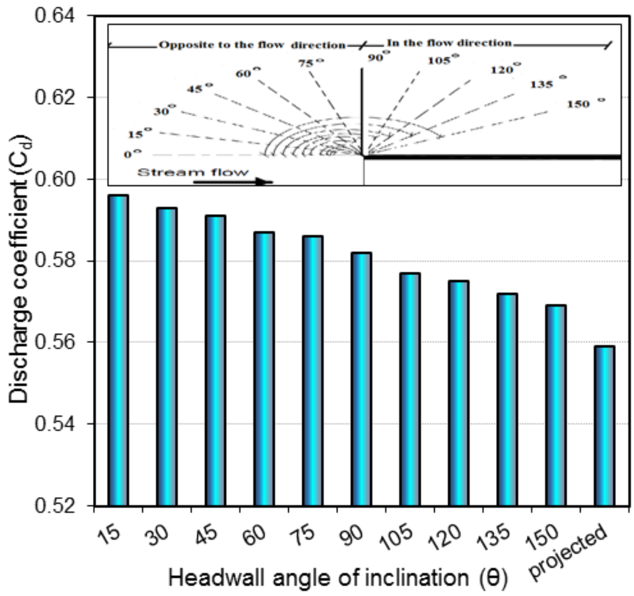


Figure 4. Relationship between the discharge coefficient and the headwall angle of inclination for the circular culvert model (case of inlet control).

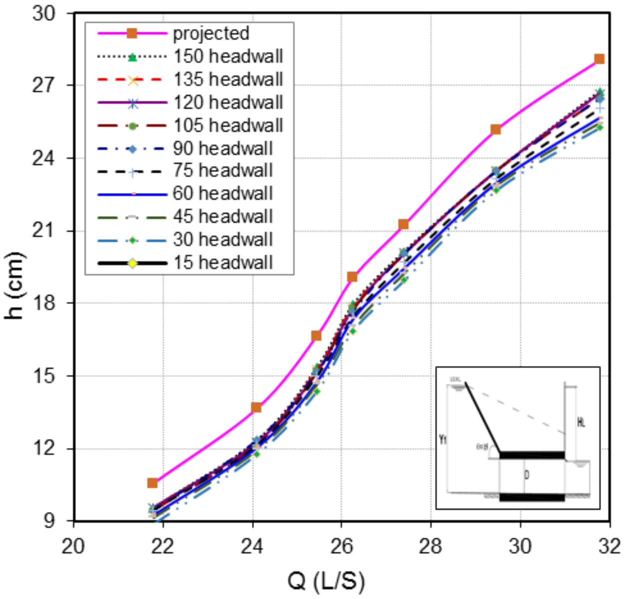
From figure (4), it is clear that using the headwalls in general improves the hydraulic performance of the culverts. Among the ten tested angles of inclination of the headwall, the angle of inclination 15° in the opposite direction of the flow gives the best results. This headwall increases the discharge by 6.7 % compared with the projected culvert model.

5.1.2 The effect of headwall inclination angle on working efficiency (case of outlet control)

In case of free outlet, the culvert end is free, and in order to explain the relationship between the discharge (Q) and the total head loss [H_L=Y_1 - D] for the different types of the tested headwalls and comparing them with the projected culvert, the values of (Q) and (H_L) were plotted as shown in figure (5), from which it can be noticed that:

- A significant reduction in the head loss was achieved by using the tested inclined headwalls compared with the projected one which allows more discharge to pass with the same U.S. water depth.
- The performance of the angles with inclination in the opposite direction of the flow was better than the performance of the angles which inclined in the direction of the flow.
- With respect to the tested headwall angles, the best angle of inclination that gives the lower water depth (minimum head loss) at the U.S. for the same discharge is angle 15° in the opposite direction of the flow, and by increasing the angle inclination from 15° to the projected (180°) the efficiency is decreased.

In case of submerged outlet, the culvert end is submerged, and to illustrate the relationship between the discharge (Q) and the total head loss [H_L=Y_1 - Y_2] for the different tested angles of headwall inclination, the values of (Q) and (H_L) were plotted as shown in figure (6).



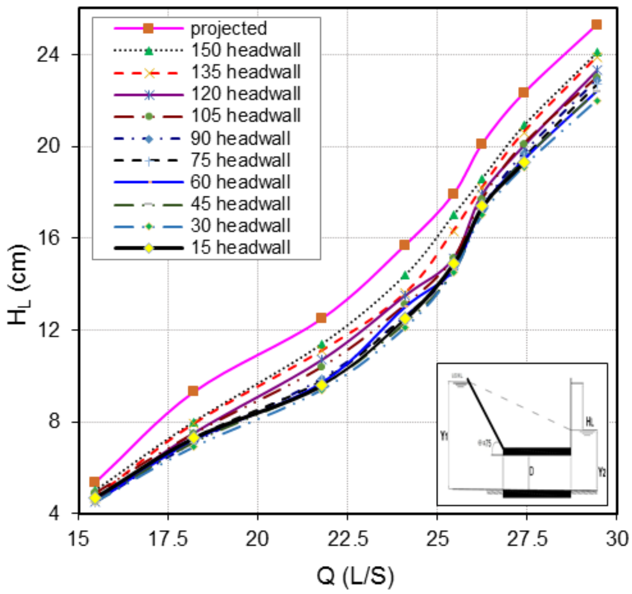


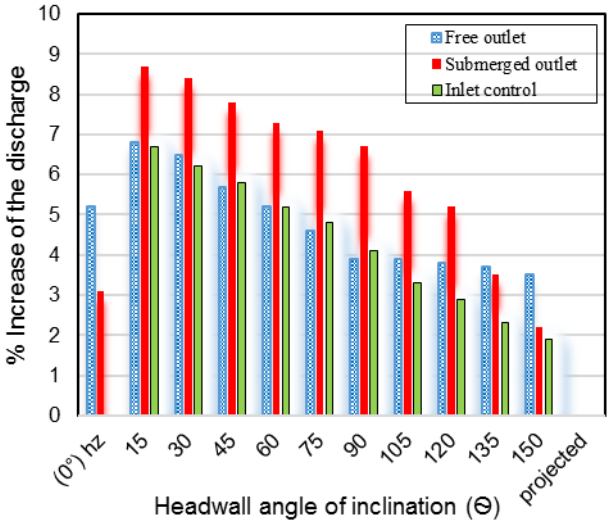
Figure 5. Relationship between the discharge and the head loss for the circular culvert (case of free outlet).

Figure 6. Relationship between the discharge and the head loss for circular culvert (case of submerged outlet).

Figure (6) clears that:

- Entrance losses through the projected culvert was higher than that for the other tested models with headwalls in general, which means that using headwalls can improve the hydraulic performance through culverts.
- Angles of headwall inclination have a great importance in improving the flow through the culvert. At the same time, the inclination in the opposite direction of the stream flow proves more influence than that in the same direction of the flow.
- The inclination angle of value of 15° in the opposite direction of the flow gives better results than the other tested angles.

Figure (7) shows the effect of the headwall angles of inclination on the discharge through the circular culvert (case of inlet control, free outlet control, and submerged outlet control), while figure (8) shows the effect of headwall inclination angle on the head loss in case of outlet control.



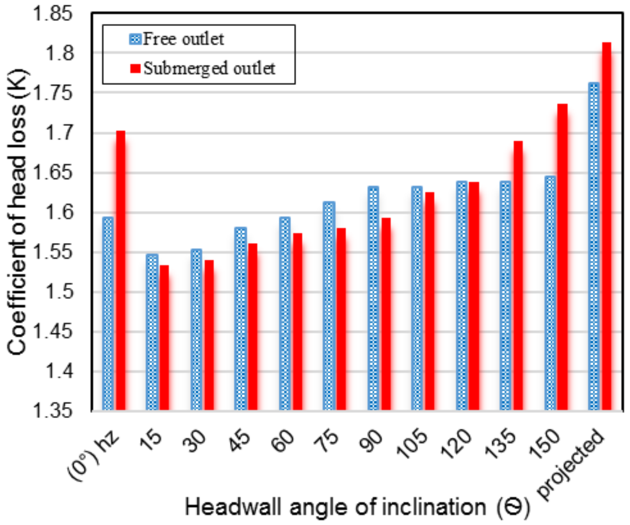


Figure 7. Effect of the headwall angles of inclination on the discharge through circular culvert (Case of inlet control, free outlet control and submerged outlet control).

Figure 8. Effect of headwall inclination angle (θ) on the coefficient of head loss (K) for circular culvert, (Case of outlet control).

From figures (3) through (8) it is obvious that, using headwall with an inclination angle of 15° in the opposite direction of the flow, gives lower water depth at the U.S. (minimum head loss) in case of outlet control. Also, it gives the best discharging efficiency in both cases of flow, inlet and outlet control.

5.2. Box culvert model

For investigating the effect of the headwall inclination on the working efficiency of the box culvert having the same cross sectional area and the same length of the circular model, the tested headwall models with the same angles of inclination were used. The obtained results were compared with the projected culvert in both cases of flow (inlet control and outlet control).

5.2.1. The effect of headwall inclination angle on the working efficiency of box culvert (case of inlet control)

The experiments showed that, the box culvert barrel is running partially full only when the culvert inlet was projected, while for the rest models a hydraulic jump was formed inside the culvert barrel and moves towards the U.S. side until the barrel becomes full and the flow changes from the inlet control to outlet control. So, the inlet control condition can be found only in the case of the projected box culvert. Thus, the effect of headwall will be studied only in case of outlet control.

5.2.2. The effect of headwall inclination angle on the working efficiency of box culvert (case of outlet control)

In case of free outlet, Figure (9) illustrates the relationship between the head loss [$H_L=Y_1-d$], and the discharge for all tested headwall models. All models gave a significant reduction in the head loss compared with the projected culvert. From the figure (9) it is noted that:

- Using headwalls turns the flow from the orifice flow (culvert flowing partially full) to the full flow, which means increasing the culvert efficiency, and the possibility of passing more discharge through the culvert barrel with the same barrel cross sectional area.
- Inclination of the headwalls in the opposite direction of the flow is more efficient than those with inclination in the same direction of the flow.
- The headwall of inclination angle 15° in the opposite direction of the flow gives the lowest water depth at the U.S. for the same discharge value which means more efficiency.

For illustrating the relationship between the discharge (Q) and the head loss (H_L) for the under study headwalls in case of submerged outlet, figure (10) was constructed, from which it is clear that using headwalls with any inclination angle improves the hydraulic performance through the box culverts comparing with the projected culvert.

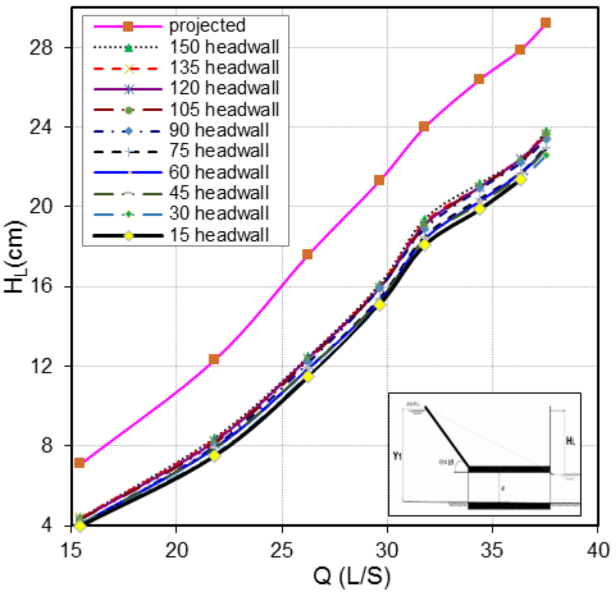


Figure 9. Relationship between the discharge and the head loss for box culvert (case of free outlet).

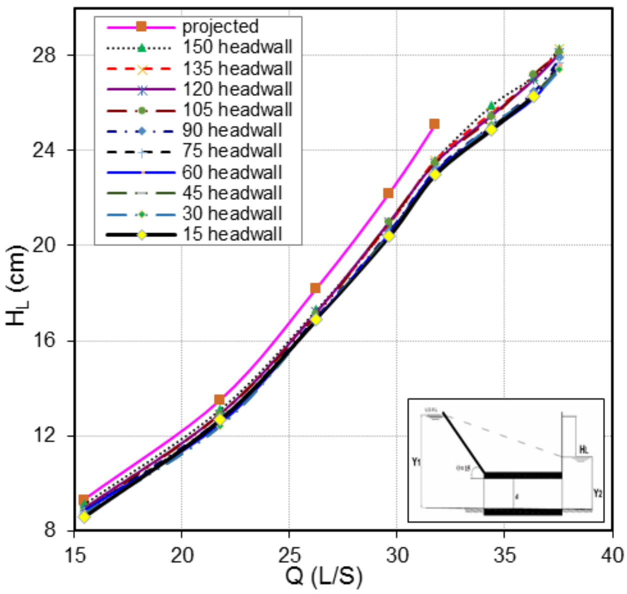


Figure 10. Relationship between the discharge and the head loss for box culvert (case of submerged outlet).

Figure (11) shows the effect of the headwall angles of inclination on the discharge of the box culvert, while figure (12) shows the effect of headwall inclination angle (θ) on the coefficient of head loss (K), in case of outlet control.

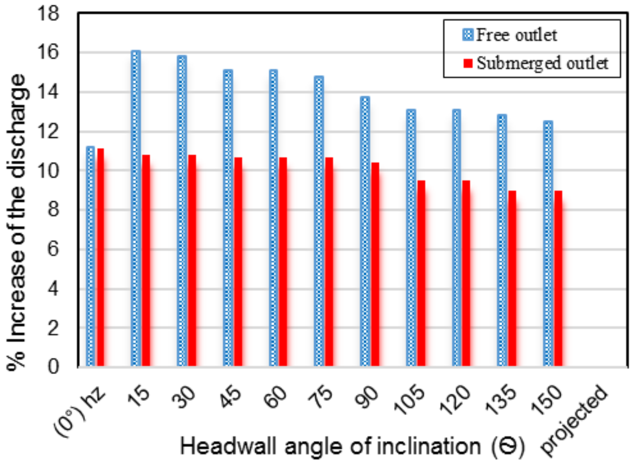


Figure 11. Effect of the headwall angles of inclination on the discharge of circular culvert (Case of inlet control, free outlet control and submerged outlet control).

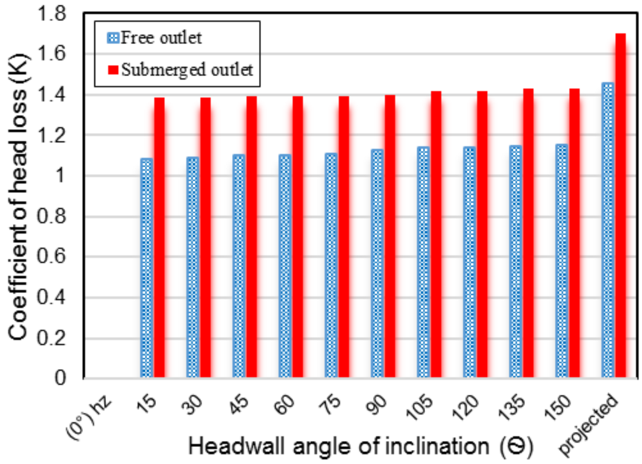


Figure 12. Effect of headwall inclination angle (θ) on the coefficient of head loss (K) for circular culvert (Case of outlet control).

Through figures (9) to (12), it is clear that, the angle of headwall inclination 15° in the opposite direction of the flow is the best angle of inclination that gives the lower water depth at the U.S. (minimum head loss) for the same discharge and gives the best hydraulic efficiency for the box culvert model.

5.3 Comparison between the obtained results with circular and box culvert examined models

From the above results it can be noticed that; for the circular tested culvert model, the inlet control condition occurred with all tested headwall inclination angles. While, for the tested box culvert model, the orifice flow occurred only with the projected culvert, and for other tested headwall models, a hydraulic jump was formed inside the culvert barrel and moved towards the U.S. side until the barrel became running full, and so the flow changed from inlet to outlet control, and the outlet control condition occurred in all under study culvert models (circular and box).

5.3.1 Relationship between the U.S. water depth and the discharge for circular and box culvert (case of inlet control)

In order to illustrate the relationship between the U.S. water depth and the discharge for the circular culvert and box culvert with the same cross sectional area and length, figure (13) was plotted for the projected model, from which it was found that, for the same U.S. water depth the discharge passing through the box culvert is higher than that passing through the circular culvert with about 10.8 %. [$Q = 0.045h^{0.5}$ for the projected circular culvert & $Q = 0.05h^{0.5}$ for the projected box culvert].

Figure (14) shows the relationship between the submergence ratio (Y_1/D) and the discharge factor ($Q/D^{2.5}\sqrt{g}$) for circular and box culvert models (dimensionless relation), from which it is clear that, the performance of the box culvert is better than the performance of the circular culvert with the same barrel cross sectional area and the same length.

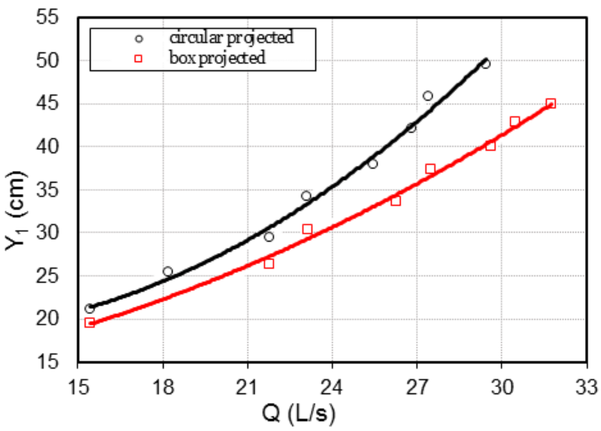


Figure 13. Relationship between the U.S. water depth and the discharge (case of inlet control).

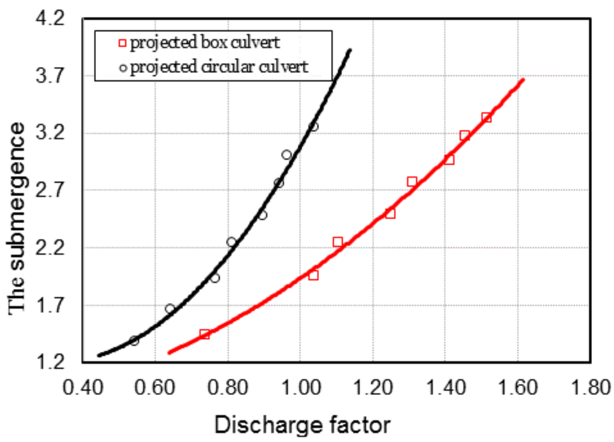


Figure 14. Relationship between the submergence ratio and the discharge factor (case of inlet control).

5.3.2. Effect of headwall angle of inclination on the discharge and head loss for circular and box (case of free outlet)

Figure (15) illustrates the percentage of increase of the discharge for all tested headwall models for the box culvert and the circular culvert, in case of the free outlet. The figure shows that, the effect of headwall on the percentage of increase in the discharge in the case of the box culvert, is more than that for the circular culvert.

Figure (16) illustrates the percentage of decrease in the head loss for all headwall models for the box culvert, the circular culvert and taper inlet circular culvert for the case of free outlet. From which it is clear that; the percentage of decrease in head loss for the box culvert is more than the circular culvert. Therefore, for the same head water depth, the box culvert passes more discharge than the circular model.

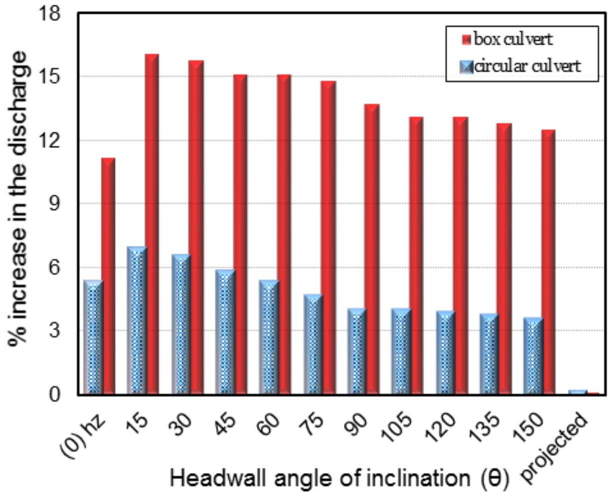


Figure 15. Effect of headwall angle of inclination on the discharge for circular, box and taper inlet circular culvert (case of free outlet).

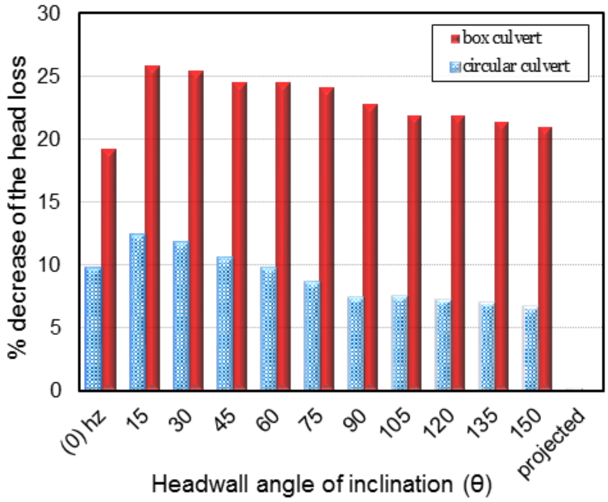


Figure 16. Effect of headwall angle of inclination on the head loss for circular, box and taper inlet circular culvert (case of free outlet).

5.3.3 Effect of headwall angle of inclination on the discharge and head loss for circular and box culvert (case of submerged outlet)

Figure (17) illustrates the percentage increase of the discharge for all used headwall models for the box culvert and the circular culvert, for the case of submerged outlet. Although the tested culvert models have the same cross sectional area, the percentage of increase in the discharge for the box culvert is better than the circular. Figure (18) illustrates the percentage of decrease of the head loss for all used headwall models for the box culvert and the circular culvert, for the case of submerged outlet. The figure shows that the percentage of decrease in head loss for the box culvert is more than the circular culvert.

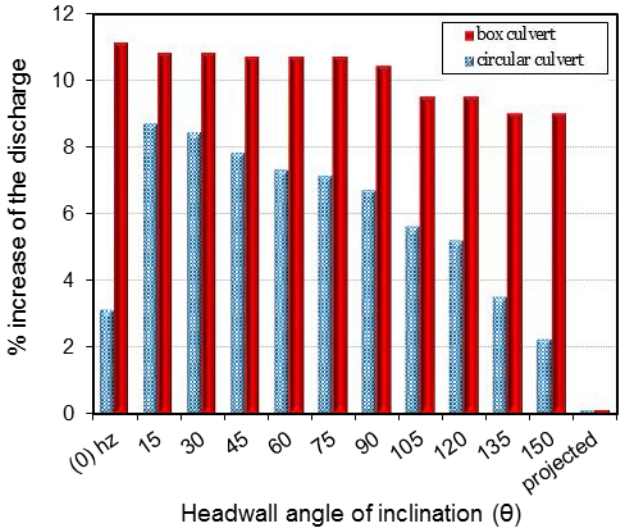


Figure 17. Effect of headwall angle of inclination on the discharge for circular, box and taper inlet circular culvert (case of submerged outlet).

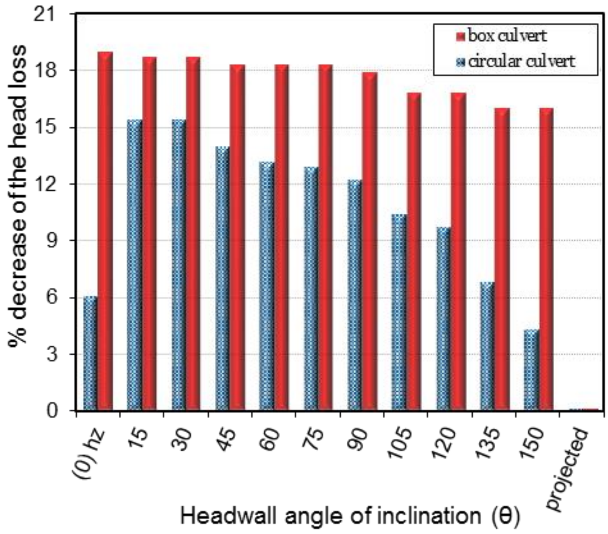


Figure 18. Effect of headwall angle of inclination on the head loss for circular, box and taper inlet circular culvert (case of submerged outlet).

Figure (18) illustrates the percentage of decrease of the head loss for all used headwall models for the box culvert and the circular culvert, for the case of submerged outlet. The figure shows that the percentage of decrease in head loss for the box culvert is more than that with the circular culvert.

6 CONCLUSION

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

- A new effective engineering tool was successfully introduced for improving the under desert road culverts, and increasing their discharging efficiency.
- The angle of the entrance headwall inclination is of great importance in increasing the discharge efficiency of the two examined types of culverts.
- Inclination of the headwall in the opposite direction of the stream flow gives better results than that with the inclination in the same direction of the flow.
- The angle value of 15° in the opposite direction of the stream flow gives better results than that obtained with other tested values of inclination angles.
- For the tested circular culvert, the 15° inclined headwall in the opposite direction of the stream flow increases the discharge by about 6.7%, 6.8%, and 8.7% for the cases of: inlet control, free outlet, and submerged outlet respectively comparing with projected culvert (without any headwall)
- For the tested box culvert, the 15° inclined headwall in the opposite direction of flow increases the discharge by about 16.1% in the case of free outlet, and by about 10.8% in the case of submerged outlet.
- A new practical equation joining the discharge coefficient (C_d) with the value of the headwall inclination angle (Θ) for culverts operate with inlet control was introduced. Also, another equation joining the head loss (H_L) with the value of the headwall inclination angle (Θ) for culverts operate with outlet control was introduced.

Notations

Q is the discharge.

C_d is the discharge coefficient.

A is the barrel cross sectional area.

g is the gravity acceleration.

H_L is the head loss.

h is the U.S. water depth measured from the axis of the barrel.

Y_1 is the U.S. water depth measured from the bottom of the barrel.

K_{in} is the entrance losses coefficient.

K_{sc} is the screen losses coefficient.

K_{fr} is the fiction losses coefficient.

K_{ex} is the exit losses coefficient.

K is the coefficient of head loss.

D is the diameter of circular culvert.

D is the height of the box culvert.

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