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Improvement of the Performance of multi-vents culvert under different flow conditions

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Abstract: The culvert is a structure that allows water to flow under a road, railway, or corridor, and it is one of the important water facilities due to its use in many practical applications. These facilities are used in crossing small waterways under roads, as well as in crossing seasonal waterways that are used to collect rainwater to resist torrential rains in rainy valleys. and their proper design is critical to ensure a safe and reliable transportation network, but there are some problems facing the structure, such as blockage, soil collapse, and closure due to the maintenance period and head losses. The performance of the culverts must be improved, the head losses must be reduced, and the best of hydraulic structure must be chosen. Where, the selection of number of pipes with area equivalent to area of one pipe and different discharges from 1.59 lit./sec to 16.88 lit/sec and various submergence ratio (1.5, 2, 2.4). the effect of the existence pipe (or pipes) culvert on the flow characteristic such as, water depth (upstream and downstream), submerged ratio, flow intensity or (pipe Froude number) and energy loss were investigated and analyzed using a series of figures to identity the best case from hydraulic point of view.
Keywords: Culvert, Submerged Ratio, Pipe Froude Number, Tail Water Depth.

1. Introduction

The culvert is a structure that allows water to flow under a road, railway, and other crossing with roads. culvert is a major water facility due to its usage in a variety of practical applications. These facilities are used to cross small waterways under roads, as well as seasonal waterways used to collect rainwater in rainy valleys to resist torrential rains. Bridges, culverts, aqueducts, and syphons are examples of crossing constructions designed to solve the problem of intersections between different water ways or between water ways and roadways. So, crossing structures play an important role in resolving the problem of these intersections; additionally, old crossing structures founded on the old network should accommodate the new excessive discharge required for feeding new canals, so old structures on the net may be replaced by a new one, which is costly, or the old structures may be rehabilitated in order to contain new discharges. culvert can be Classified according to shape as (square, rectangular, circular, arch culvert) and according to material as (steel, concrete and pvc).

Culverts are an important part of drainage networks worldwide, providing an efficient solution for flowing water to overcome man-made obstacles such as roads. However, it was found that only smooth and short culverts with high entrance losses would benefit from this approach, and many existing structures could be improved with better entrance design. Hydraulic improvements to existing culverts to increase flow rates may be a cost-effective alternative to rebuilding any failed structures **[1]**.

They investigated the differences between open channel flow and hydraulic culvert design; they stated that sediment transport through culverts is poorly understood, and they identified and classified the major differences between open channel flow conditions and flow through a culvert embedded in native substrate. Flow characteristics differ most easily when divided into four categories: geometry, sediment/debris, bed integrity, and aquatic life **[2]**.

Local scour downstream the box culverts outlet may cause to a complete failure of the culvert structure. A sharp edge sill is proposed on a rigid bed to dissipate the flow excess energy. Consequently, a great reduction of the scour hole dimensions is obtained by using the sharp edge sill. The experimental study was carried out using a different positions, heights and shapes of the sharp edge sill with different flow rates as well as tail water depths too. The results indicates that the sharp edge sill is a promising tool to reduce the scour dimensions **[3]**.

While we cannot completely avoid watercourse crossing failures, we can reduce failure potential through careful crossing design that accommodates water, wood, and sediment and that reduces potential erosional consequences if and when they do fail **[4]**.

Produce experimental work aims to study the velocity distribution along inverted syphon using ultra sonic device, concerning pipe flow the velocity is found to be affected by the elbow located upstream from the test section. Flow leaving the elbow is distorted and returns to an undistorted velocity profile after a certain pipe length (6 to 10 times the pipe diameter D). If the test section is located within that zone, the computation of the flow rate is likely to be incorrect **[5]**.

When determining if a culvert is needed at a crossing site, an on-site evaluation is performed. However, there are alternative options such as hardened seasonal fords, rock armored crossings, or drain swales that may be more appropriate due to their low maintenance and ability to be constructed without introducing fill into the stream channel. The appropriateness of these designs is influenced by various crossing site characteristics such as stream channel depth, flow velocities, stability, gradient, bank steepness, and approaching road grades **[6]**.

Presented a versatile two-parameter model describing the hydraulic performance of highway culverts operating under inlet control for both unsubmerged and submerged conditions. Applications show that the model can accurately represent the Federal Highway Administration performance curves (which use four parameters) for a range of culvert types and materials **[7]**.

A new flow rating algorithm called SEM has been developed for computing flow in weir box culverts. This method separately calculates flow discharges while maintaining discharge continuity, resulting in accurate water stage identification and reasonable flow computational results. The algorithm can also be extended to compute flow for other types of compound culverts. Weir box culverts are challenging to compute flow for using traditional culvert flow equations due to their configuration **[8]**.

Proposed experimental study for better understanding of the influence of slip-lined culvert inlet end treatment geometry on discharge capacity, The tapered projecting inlet was as much as 7% more efficient under inlet control and approximately 12% more efficient (entrance loss coefficient reduction) under outlet control, relative to the non-tapered projecting inlet condition **[9]**.

Inlet control can be achieved by various combinations of inlet and outlet submergence. output control can also occur when the inlet and output are submerged or not. The position of the effective control, the significance of 'minor' energy losses, and the effect of inlet submergence must all be considered while analyzing culverts **[10]**.

The hydraulics and discharge characteristics of sharp-crested weir culverts with downstream ramps were investigated in the laboratory for hydraulically smooth wall boundary and free, partially submerged, and completely submerged-flow circumstances. Energy losses across weir-culvert models were computed as well, and they reduced with submergence. Four weir-culvert models with varying weir heights, ramp lengths, and culvert heights were examined **[11]**.

The treatment of the longitudinal boundaries of the track results in an energy loss comparable to the reference configuration with smooth boundaries. Compared to the literature on box culverts, research on the passage of low-body fish species in pipe culverts is relatively limited. For small and juvenile fish, excessive running speed is often a major obstacle due to weak swimming ability **[12]**.

At the same time, it also provides some necessary design and construction guidelines for structural safety during the backfilling process of buried corrugated steel pipe culverts. Based on the measured stress data of corrugated steel plate porous continuous pipe elbow culvert, the proposed three-dimensional finite element method and stress evolution law were verified. Although in-depth research has been conducted on buried corrugated steel pipe culverts in recent decades, the stress evolution law between the wave crests and troughs during the backfilling process is still not fully analyzed, which is an important technical difficulty in the construction of this type of structure **[13]**.

The long-term hydraulic project was challenged by changes in weather conditions and trends, leading to changes in emissions that were not anticipated in the original design of the structure. Flow rates higher than those anticipated in the original design may result in damage to the infrastructure itself and to upstream properties. Culverts are a common solution where man-made transportation routes intersect natural waterways. The aim of this study is to find effective ways to significantly improve the drainage capacity of existing culverts to meet new hydrological parameters without having to rebuild them **[14]**.

Engineering structures built on soft and compressible soils often suffer from long-term consolidation settlement. Numerical analysis shows that the finite element results are in good agreement with the on-site settlement monitoring data, with the maximum deviation being only 0.0305 meters, and the numerical analysis results remain large during most of the consolidation period. The critical effect of wick runoff and some key parameters (fill thickness and wick runoff distance) were also investigated **[15]**.

2. Experimental Work:

The experiment work was carried out on a channel located in the hydraulic lab at Al-Azhar University. We needed to work on creating a test channel model for experimentation runs.

The 8-meter-long channel was divided into three components. The first and last sections are 3-meter-long, 60-Centimeter-wide, and 30-Centimeter-high. The third section is 2-meter-long, 60-Centimeter-wide, and 40-Centimeter-high, with the middle curved at a 30-degree angle on the horizontal.

The flume is made of steel with visible polycarbonate sides. The raging floor measures 60-Centimeter in length. It is made of Perspex to avoid distortion due to water action. the discharge was measured using well-calibrated rectangular sharp crested weir.

2.1 Design culvert:

the experimental models are pvc material with circular crossing with different numbers and diameters:

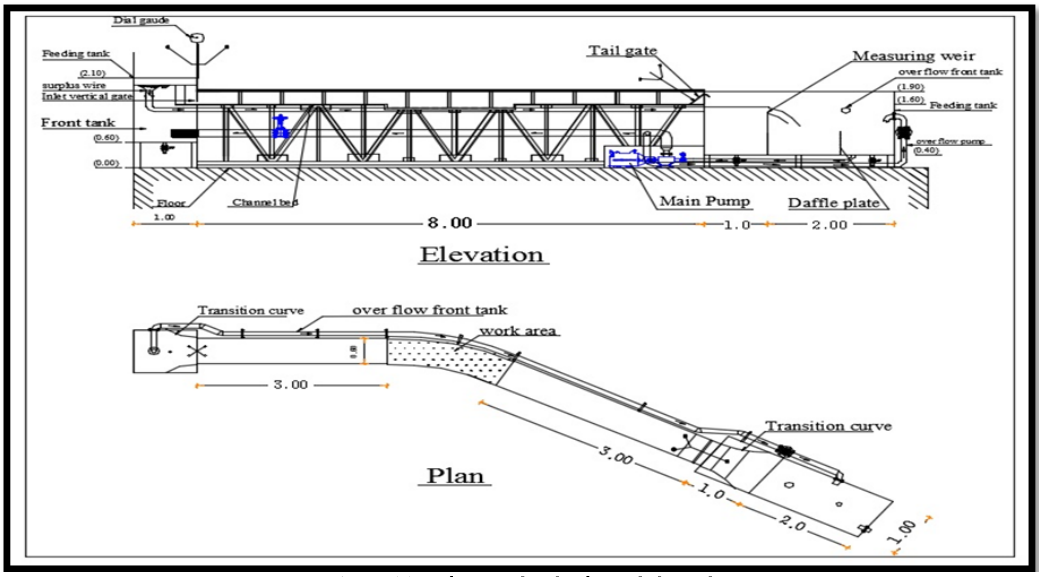

Figure (1) Definition sketch of tested channel

Figure (2) Measuring weir

Cases	Diameters of pipes (cm)	Numbers of pipes	Area (cm^2)	B_T (cm)
Case 1	10	1	78.5714	11.5
Case 2	5	4	78.5714	26
Case 3	10	2	157.143	23
Case 4	5	8	157.143	52

Where, B_T= (D+1.5) * N ≤ B_c=60 cm B_t: Total width of pipes
D: Diameters of pipes N: Numbers of pipes
B_c: Width of culvert

Nine pipes installed with a diameter of 5 cm and a length of 100 cm between the two slabs, and also 4 pipes with a diameter of 10 cm and a length of 100 cm between the two slabs, which are fixed by silicone material, then the whole model is installed in the middle of last part of channel and Water passing through pipes. as indicated in fig (3) to (5).

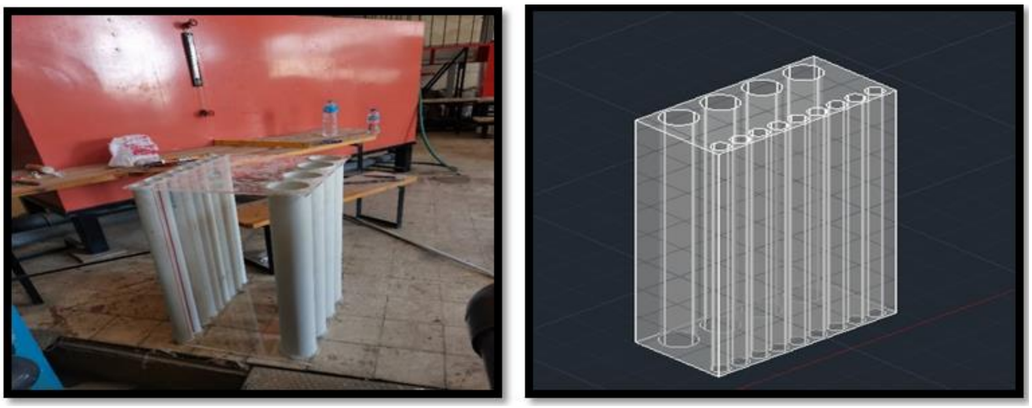

Figure (3) form the model

Figure (4) Installing the model in the flume

Figure (5) Water passing through pipe

3. Numerical Simulation:

The current culvert research is simulated with FLOW-3D software (98), a powerful computational fluid dynamics (CFD) program.

FLOW-3D, a highly powerful multi-physics tool, provides the functionality, simplicity, and capacity that engineers require to achieve their modeling objectives. FLOW-3D is engineered for maximum performance and seamlessly scalable from traditional workstation solutions to high performance computing cluster systems with hundreds of CPU cores.

3.1 Geometric Presentations:

For any change in culvert geometry and dimensions, a stereolithographic (STL) file is created.

As shown in Fig (6), CAD programs are useful for designing solid objects and converting them to (STL) format.

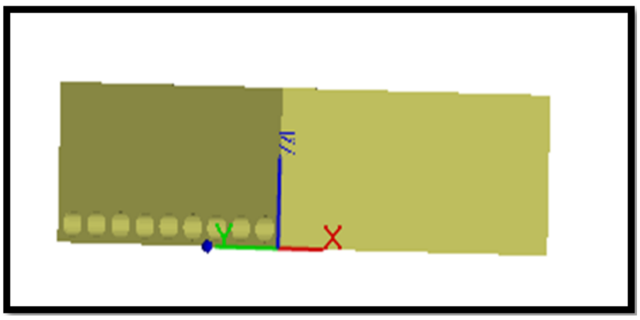

Figure (6) CAD solid geometric file

3.2 Governing Equations:

The Flow-3D V. 11.1.1 (2015) application is used in this study to simulate the flow of water inside the culverts. The governing equations for the motion of an incompressible viscous fluid are the Reynolds-averaged Navier-Stokes (RANS) equations.

The continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0$$

The momentum equation:

$$\frac{\partial u_i}{\partial t} + \frac{1}{V_F}\left(u_j \frac{\partial u_i}{\partial x_j}\right) = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[-p\delta_{ij} + \nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho\overline{u'_i u'_j}\right]$$

Where, u is time averaged velocity, ν is kinematic viscosity, V_F is fractional volume open to flow, p is averaged pressure and $-\overline{u'_i u'_j}$ are component of Reynold's stress. The volume of fluid (VOF) technique is used to simulate free surface profile. The Renormalized group (RNG) model is used to simulate turbulence characteristics. The sediment transport processes which include bed load transport, suspended load transport, entrainment and deposition are simulated by using the sediment scour model

3.3 Boundary and initial Conditions:

The boundary conditions should be carefully specified to improve the accuracy of the results. In this study, one mesh block is employed to reduce the time used for simulation. The following are the boundary conditions for one mesh block: The inlet is defined as a volume flow rate condition, the outlet is defined as a specific pressure condition with used to fluid elevations with different values, the bottom and sides boundaries are defined as a wall boundary condition (wall boundary condition is usually used for bound fluid by solid regions. In the case of viscous flows, no-slip means that the tangential velocity is equal to the wall velocity and the normal velocity is zero) and the top boundary is defined as a specific pressure boundary condition with assigned atmospheric pressure as shown in figure (7). Configuration, temperature, velocities, and pressure distribution are the starting conditions that must be specified for the fluid (i.e., water) inside the domain. The water configuration is determined by the dimensions and shape of the culvert. While the following conditions have been assigned: The temperature is normal (25ºc), and the pressure distribution is hydrostatic with no initial velocity.

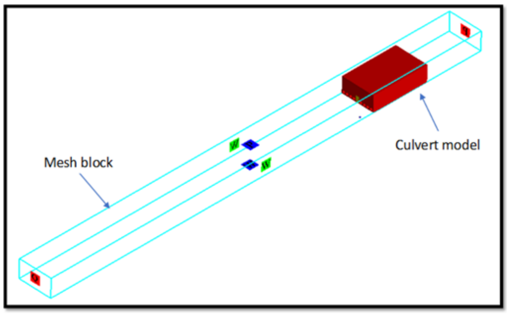

Figure (7) Boundary Conditions for the mesh block

3.4 Meshing and Geometry:

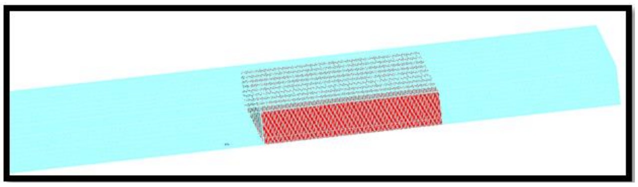

Figure (8) Mesh Block

In the X-direction, the total length of the model is 1m. the mesh block consists of four mesh planes which are adjusted at distances -6.00, 0.00, 1.00 and 2.00 m with uniform cell size 0.01m.

In the Y-direction, the total width of the model is 0.60m. the mesh block consists of several different mesh planes which are adjusted at variable distances in each independent case due to the different numbers and diameters of the pipes used.

In the Z-direction, the total height of the model is 0.30m. the mesh block consists of five mesh planes which are adjusted at distances p1= 0.00m, p2= 0.01m, p3= (0.06 or 0.11) m This value varies due to the different diameters of the pipes used (0.05 or 0.1) m, p4= 0.3m and p5= 0.35m with a uniform cell size of 0.01m as shown in figure (9).

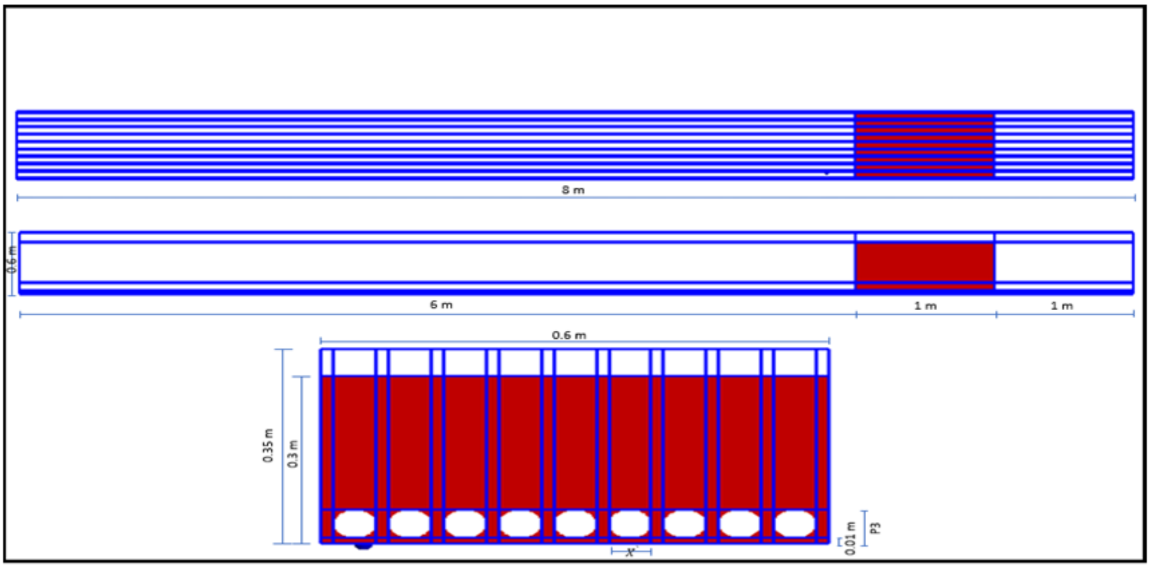

Figure (9) Mesh Blocks Dimensions in FLOW-3D

4. Analysis and Discussions:

4.1 Experimental work:

The results of the experiment are presented, analyze and discussed in this work. All dimensionless variables; out from the dimensional analysis, were used to clarify the relationships between the pipe Froude number (Fp), relative tail water depth (Yd/Yup), relative head loss (ΔY/Yup), relative energy loss (ΔE/Eup) and relative Upstream Water Depth (Yup/D) for cases (1 to 4).

the main idea of this study is the selection of number of pipes with area equivalent to area of one pipe. the effect of the existence pipe (or pipes) culvert on the flow characteristic such as, water depth (upstream and downstream), submerged ratio $\frac{Y_{d.s}}{D}$, flow intensity (pipe Froude number Fp) and energy loss were investigated and analyzed using a series of figures to identity the best case from hydraulic point of view.

4.1.1 Relative tail water depth:

Case (1):

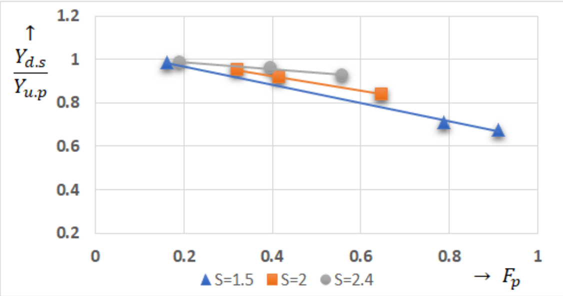

Figure (10) Relationship between pipe Froude number and relative tail water depth for deference submerged ratio (Case-1)

Case (2): It represent the same area as the previous case (1d10).

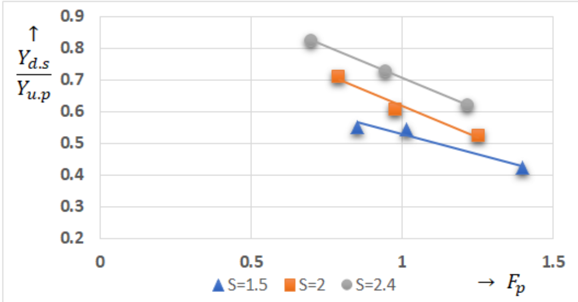

Figure (11) Relationship between pipe Froude number and relative tail water depth for deference submerged ratio (Case-2)

At the same area (A=78.5714) cm^2, a comparison is made between cases: 1d10 (number of pipes =1 and diameter of pipe =10 cm) and 4d5 (number of pipes =4 and diameter of pipe =5 cm) with different submerged ratio.

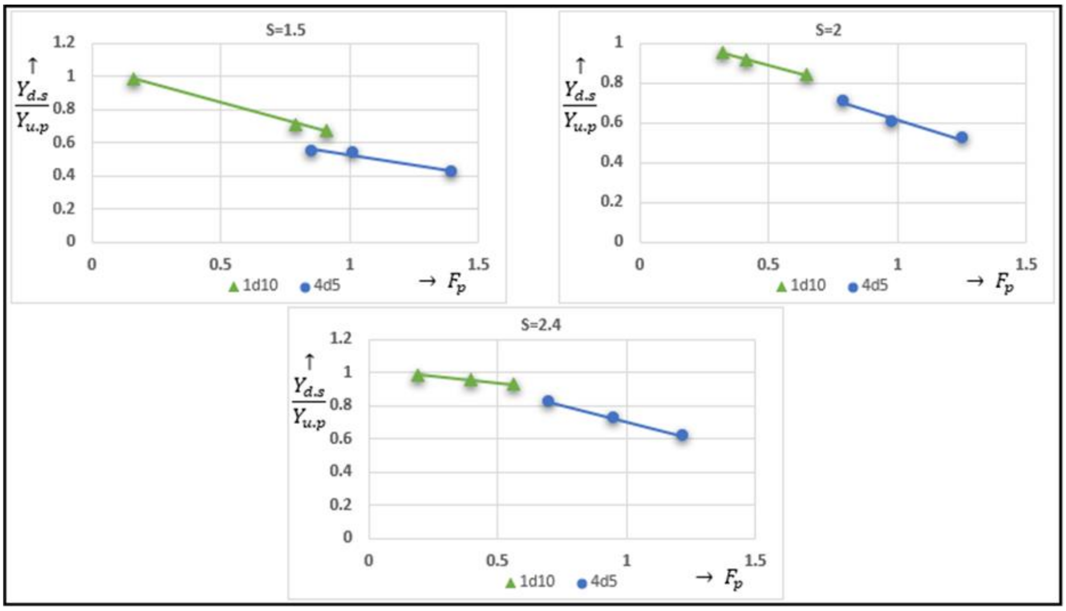

Figure (12) Relationship between pipe Froude number and relative tail water depth for deference submerged ratio for 1d10 and 4d5

When making a comparison between the two different cases in terms of the number and diameter of pipes when they have the same area and different submerged ratio, we find that the first case (1) It is the best hydraulically because the average velocity in the two cases is close to each other and the first case is the lowest in the wetted Perimeter (10πD).

Case (3):

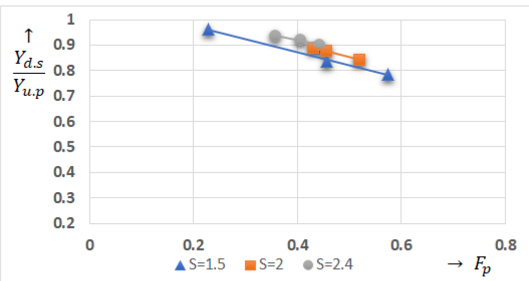

Figure (13) Relationship between pipe Froude number and relative tail water depth for deference submerged ratio (Case-3)

Case (4): It represent the same area as the previous case (2d10).

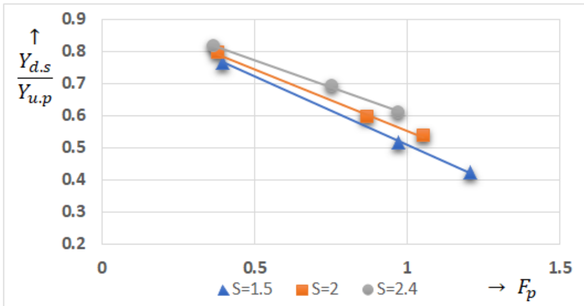

Figure (14) Relationship between pipe Froude number and relative tail water depth for deference submerged ratio (Case-4)

At the same area (A=157.143) cm^2, a comparison is made between cases: 2d10 (number of pipes =2 and diameter of pipe =10 cm) and 8d5 (number of pipes =8 and diameter of pipe =5 cm) with different submerged ratio.

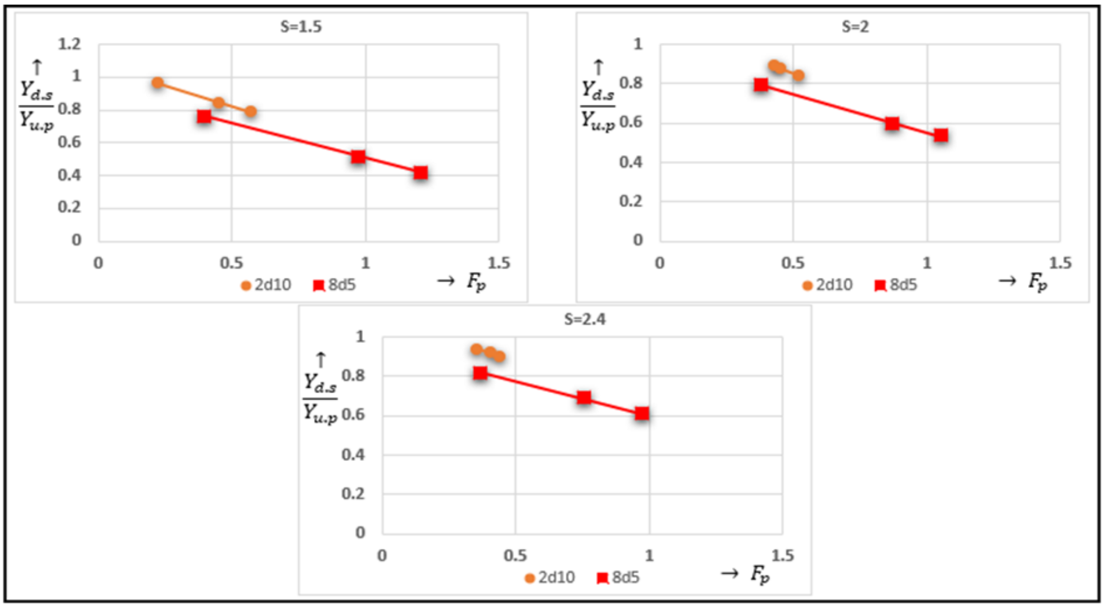

Figure (15) Relationship between pipe Froude number and relative tail water depth for deference submerged ratio for 2d10 and 8d5

When making a comparison between the two different cases in terms of the number and diameter of pipes when they have the same area and different submerged ratio,

we find that the first case (3) It is the best hydraulically because the average velocity in the two cases is close to each other and the first case is the lowest in the wetted Perimeter (20πD).

From the previous cases It can be noticed that the relationship between pipe Froude number and relative tail water depth for different pipe submergence ratio and different area. From these figures, as the pipe Froude number increases the relative tail water depth decreases for all submergence ratio. Moreover, for a certain value of pipe Froude number, the relative tail water depth magnifies by increasing of the submergence ratio.

4.1.2 Relative head loss $\frac{\Delta Y}{Y_{u.p}}$ and Relative energy loss $\frac{\Delta E}{E_{u.p}}$:

<u>Case (1):</u>

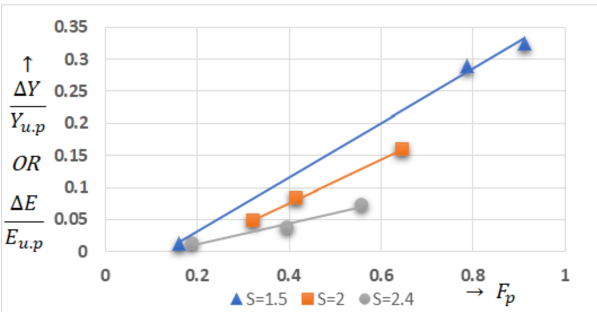

Figure (16) Relationship between pipe Froude number and relative head loss or relative energy loss for deference submerged ratio at 1d10 (Case-1)

<u>Case (2):</u>

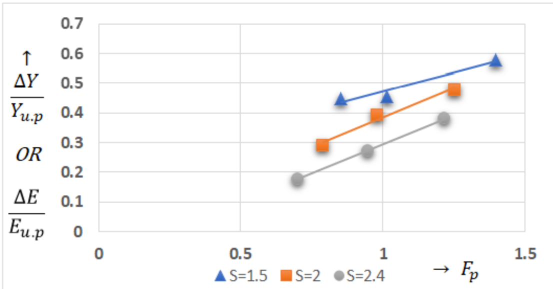

Figure (17) Relationship between pipe Froude number and relative head loss or relative energy loss for deference submerged ratio at 4d5 (Case-2)

<u>Case (3):</u>

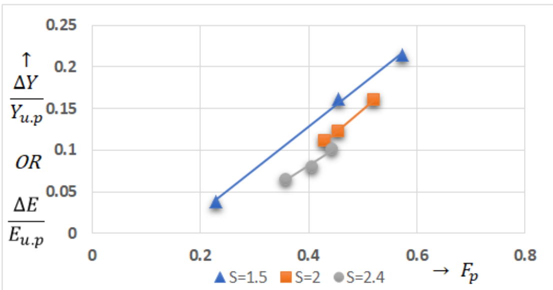

Figure (18) Relationship between pipe Froude number and relative head loss or relative energy loss for deference submerged ratio at 2d10 (Case-3)

<u>Case (4):</u>

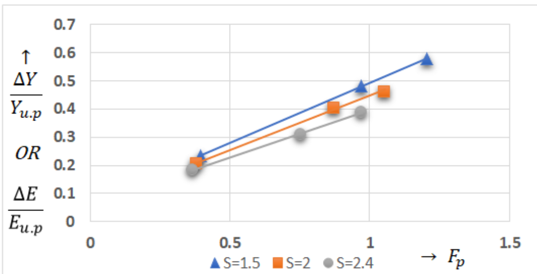

Figure (19) Relationship between pipe Froude number and relative head loss or relative energy loss for deference submerged ratio at 8d5 (Case-4)

From the previous cases that resulting from the relative head loss and relative energy loss are can be noticed that the relationship between pipe Froude number and the relative head loss and relative energy loss at different values of submerged ratio. are can be obtained that the relative head loss and relative energy loss increases with the increase of pipe Froude number for all cases of submerged ratio.

4.1.3 Relative Upstream Water Depth:

<u>Case (1):</u>

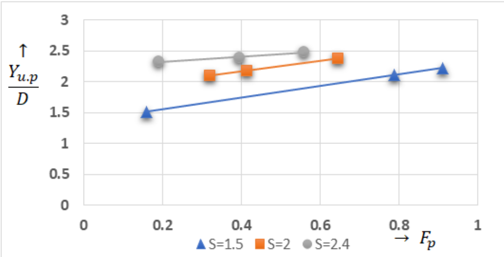

Figure (20) Relationship between pipe Froude number and Relative Upstream Water Depth for deference submerged ratio at 1d10 (Case-1)

<u>Case (2):</u>

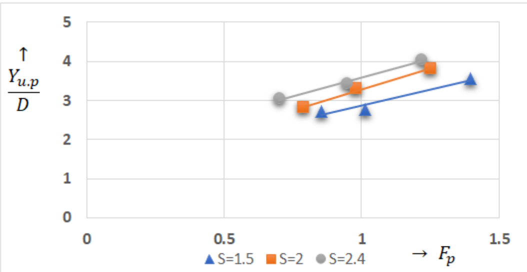

Figure (21) Relationship between pipe Froude number and Relative Upstream Water Depth loss for deference submerged ratio at 4d5 (Case-2)

<u>Case (3):</u>

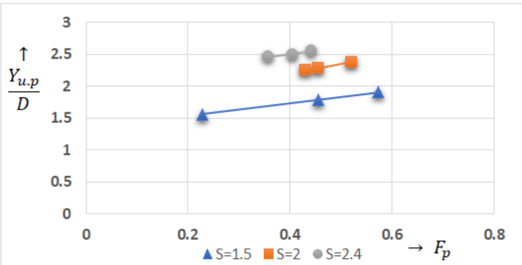

Figure (22) Relationship between pipe Froude number and Relative Upstream Water Depth loss for deference submerged ratio at 2d10 (Case-3)

<u>Case (4):</u>

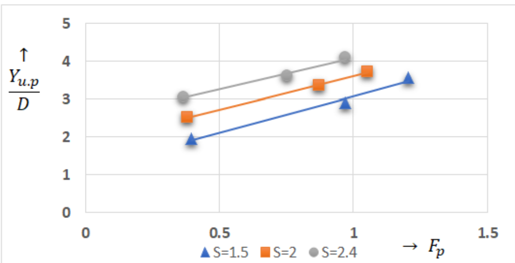

Figure (23) Relationship between pipe Froude number and Relative Upstream Water Depth loss for deference submerged ratio at 8d5 (Case-4)

From the previous cases that resulting from the Relative upstream water depth It can be noticed that the relationship between pipe Froude number and the relative Upstream Water Depth at different values of submerged ratio. It can be obtained that the relative Upstream Water Depth increases with the increase of pipe Froude number for all cases of submerged ratio.

4.1.4 Final equation:

the purpose of final equation is produced an empirical equation that links the different variables that control the phenomenon in a non-dimensional form that is easy to apply in the fields of nature.

The final equation is:

$$\frac{\mathrm{Y_{u.p}}}{\mathrm{D}} = (0.93795 \times \mathrm{S}) + \left(1.62038 \times \mathrm{F_p}\right) + (0.989883 \times \mathrm{C}) - 0.598$$

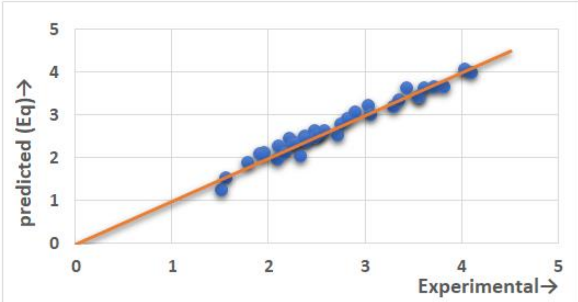

Figure (24) Relationship between Experimental and predicted results

The empirical equation that was deduced is applied to different results to ensure the success of the equation or not. for improving the accuracy of predicted equation as all results of this equation were compared with previous experimental works **[3]**. The shape factor was calculated in order to convert the box culvert to the pipe shape and was multiplied it in all the results.

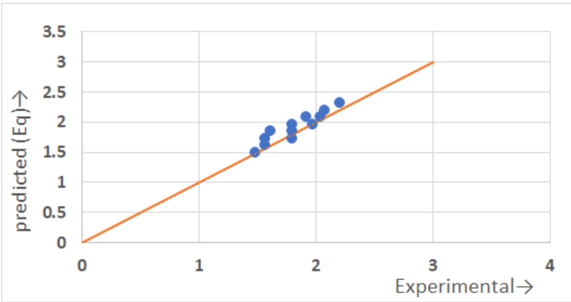

Figure (25) Relationship between Experimental and predicted results of (previous experimental works)

4.2 Numerical Work:

Flow 3D program was used to simulate Experimental work, verify the accuracy of these results, and make a comparison between them.

4.2.1 relative tail water depth:

<u>Case (1):</u>

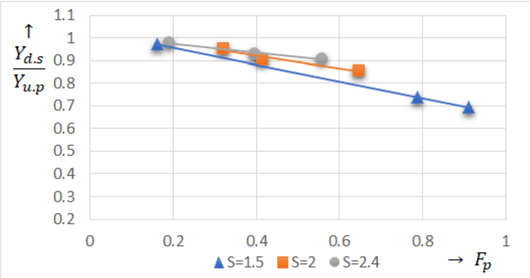

Figure (26) Relationship between pipe Froude number and relative tail water depth for deference submerged ratio (Case-1)

Case (2):

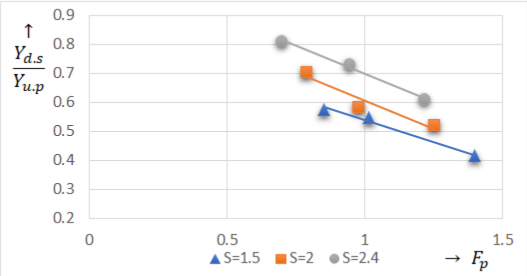

Figure (27) Relationship between pipe Froude number and relative tail water depth for deference submerged ratio (Case-2)

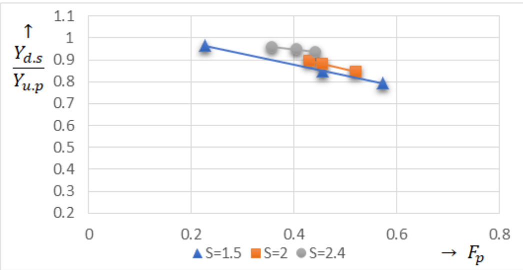

Figure (28) Relationship between pipe Froude number and relative tail water depth for deference submerged ratio (Case-3)

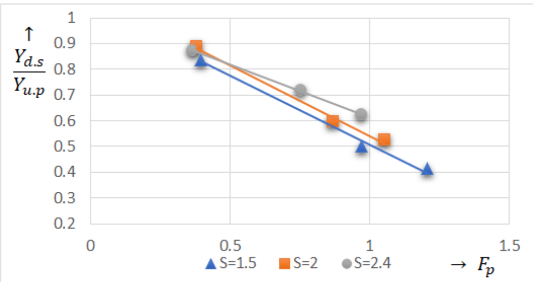

Figure (29) Relationship between pipe Froude number and relative tail water depth for deference submerged ratio (Case-4)

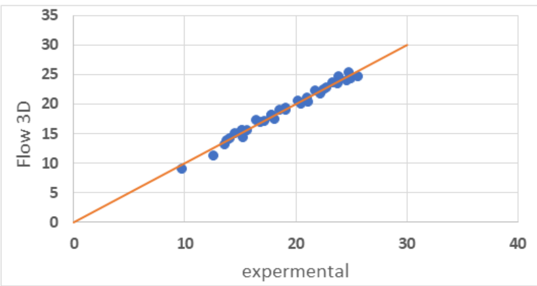

Figure (30) Relationship between the experimental and Flow 3D results of pipe culvert

5. Conclusions:

The culverts' performance must be improved, head losses must be decreased, and the best hydraulic structure must be adopted. Where the number of pipes is chosen to be equal to the area of one pipe, with discharge rates ranging from 1.59 lit/sec to 16.88 lit/sec and varied submergence ratios (1.5, 2, 2.4). The impact of the presence of a pipe (or pipes) culvert on flow characteristics such as water depth (upstream and downstream), submerged ratio, flow intensity or (pipe Froude number), energy loss was investigated and analyzed using a series of figures to determine the best case from a hydraulic behavior and the following are the summarized of work results.

1) With the increase of pipe Froude number (Fp), the relative tail water depth decreases for all submergence ratios (1.5, 2, 2.4) and the relative head losses, relative energy losses and relative upstream water depth all increase when pipe Froude number (Fp) increases because all submergence ratios decrease.

2) The upstream water depth increases mainly as a result of increasing the downstream water depth, which causes back pressure on the downstream side, resulting in an increase in upstream depth in the form of ($\frac{Y_{u.p}}{D}$).

3) Relative downstream submerged ratio ($\frac{Y_{d.s}}{D}$), plays an important role in the increasing of water depth on the upstream side of the culvert, more than the effect of increasing velocity, which performs the value of pipe Froude number (Fp).

4) the upstream velocity (Vu.p),which characterized by small value, it can be explained that the increase of upstream initial energy (Eu.p) results basically from the increase of upstream water depth (yu.p), because of the small value of upstream velocity (Vu.p) led to a small value of kinetic energy term in the energy equation especially for values less than unit.

5) We find that the basic cases (1 or 3) are better than the alternative cases (2 or 4) hydraulically because the average velocity in the two cases is close to each other and the first case is the lowest in the wetted Perimeter.

6) When the upstream water depth high, the velocity will decrease.

7) FLOW-3D program was used to simulate Experimental results, verify the validity of these results, and make a comparison between them.

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