Original Research Article

STRUCTURAL BEHAVIOR OF WEIRS WITH BOTTOM CIRCULAR OPENINGS

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ABSTRACT

Weirs are important hydraulic structures which are widely used for many purposes. Recently, due to the expansions of agriculture areas, the need for irrigation water increased, and hence there is a need to increase the discharge capacity of canals. In canals with weir systems, as in Fayoum region in Egypt, water distribution to sub-channels depends on their upstream water head (i.e. any change in water levels will disturb water distribution to sub-channels along it). Also, changes of the flowing discharge affect water levels over weirs and consequently affect the backwater curves upstream of them. Hence, to increase the discharges, weirs should be reconstructed to guarantee water levels over sub-channels' intakes. That will be very costly; which gave great importance to study, from a hydraulic and structural point of views, the possibility of making openings in weirs, to increase the discharge passing through them.

Aims: This research studies the structural behavior of rectangular Fayoum standard type weirs, with one bottom circular opening at their middle. The main goal of this research is to predict the maximum tensile, the maximum compressive, the maximum shear stresses on the weir body to know the possibility of establishment of a bottom circular opening in the middle of the existing weirs.

Methodology: The research is based on numerical analysis of weirs with different dimensions using ANSYS Fluent and ANSYS Mechanical applying Fluid Structure Interaction techniques. Results of the model were validated with experimental results from previous studies. The research results were used to develop regression equations between weir dimensions, opening diameter and flow discharge with maximum tensile stress, σ_{max}, maximum compressive stress, σ_{min}, maximum shear stress, τ_{max}, and maximum deformation, δ_{max}, occurring on the weir body.

Results: There are clear correlations between the stresses on the weir, including maximum tensile, maximum shear and maximum compressive stresses, and the dimensions of the weir and its opening diameter. Hence, the multiple regression analysis was applied to predict the maximum stresses and the maximum deformation based on the dimensions of the weir, the pipe diameter and the discharge passing in the channel.

Conclusion: Four formulae were developed to predict the values of maximum tensile stress, maximum shear stress, maximum compressive stress, and maximum deformation around circular openings in Fayoum type weirs. By comparing the stresses values with the allowable strength of concrete, the allowable opening diameter could be determined for each case.

Keywords: [Weir openings – Fluid Structure Interaction – Structural behavior – Hydraulic structures – Computational Fluid Dynamics]

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1. INTRODUCTION

Weirs are hydraulic structures which are used, among other purposes, for proper distribution of water to irrigation canals, for reducing the water surface slope in the canals and for reducing the acting head on regulators and other hydraulic structures [1, 2]. Weirs could be classified according to the shape of crest to rectangular weirs, cippoletti weirs, triangular weirs and arched weirs. Furthermore, weirs could be classified according to crest width to solid-broad-crested weir, solid-narrow-crested weirs, sharp-crested weirs and ogee weirs [3]. The Fayoum depression, located in Egypt, has a special system of irrigation due to its topography, where a system of weirs along the canals was traditionally used to regulate the slope of the canals depending on the natural terrain slope [4].

The Fayoum standard weir, widely used in Egypt, is essentially a narrow-crested rectangular weir. It consists of a rectangular control section placed in a wall across an open channel. Its crest surface makes a sharp 90-degree intersection with the upstream weir face. The crest is made of carefully aligned plain concrete. The common crest length of the weir (L=0.50 m) and the common crest slope is (H:V = 1:2) [5]. Recently, due to the expansions of agriculture areas, the need for irrigation water increased, and hence there is a need to increase the discharge passing through canals. That gives great importance to study weirs with openings to increase the discharge passing through the weirs.

Abdel Halim et al. [8] studied experimentally the characteristics of flow over Fayoum weirs with such bottom orifices. They indicated that the average value of discharge coefficient for combined structure (weir and orifice) was found to be 0.625. Mohamed et al [6] carried out an experimental study to investigate the overflow above a weir with bottom circular opening. It was found that the system having bottom pipes can pass more discharge and there are large differences between the hydraulic behavior of weirs with bottom pipes and weirs without any pipe. El-Belasy [7] developed new formulae for weirs with two pipes by modeling of some selected Fayoum weirs using SOBEK 1D model. The model was verified with field measurements. It was stated that the new formulae would assist engineers in designing the modifications required to reshape the existing weirs in order to increase the passing discharge.

This research aims to investigate the structural consequences of providing a bottom circular opening in Fayoum standard weirs to convey increased discharge using fluid structure interaction models. It aims also to develop equations to predict the maximum tensile, the maximum compressive, the maximum shear stresses and the maximum deformation due to this opening. The maximum tensile stress, σ_{max}, is the maximum principal stress generated on the weir body. The maximum compressive stress, σ_{min}, is the minimum principal stress on the weir body. The maximum shear stress, τ_{max}, is the maximum shear stress on the weir body. The maximum deformation, δ_{max}, is the maximum value of the total deformation occurred in the weir body.

Fluid structure interaction (FSI) is a multi-physics phenomenon which occurs in a system where flow of a fluid causes a solid structure to deform which changes the boundary condition of the modeled fluid system. This can also happen the other way around where the structure makes the fluid flow properties to change. This kind of interaction occurs in many natural phenomena and man-made engineering systems. FSI simulations could be performed physically or numerically. The rapid development of computer industry is also providing more and more powerful computing ability for numerical simulation, which also makes numerical simulation more applicable to a wider fields and more complex problems such as FSI problems. Unlike physical simulation which has time and space limitations, numerical techniques can simulate a very large scale region and last an almost unlimited long period of time. Numerical simulation can deal with many physical processes at the same time. Even nonlinear processes pose no difficulty to numerical simulation [19].

FSI simulations also could be conducted to avoid flutter on aircraft and turbo-machines [9], to evaluate the environmental loads and dynamic response of hydraulic structures [10, 11] and in many bio-medical applications [12]. Recently, many commercial software packages

are being developed and established to simulate FSI problems. Software packages / developers, like ANSYS [13], ADINA [14], COMSOL [15] and CD-Adapco [16] provide efficient multi-physics softwares with versatile features.

2. METHODOLOGY

In this research, the FSI analysis has been conducted on a standard Fayoum weir with one bottom circular opening. The fluid and structural models have been created with appropriate dimensions. For the Fluid model, ANSYS Fluent [13] is used to simulate the flow through the weir taking into account the factors affecting the hydrodynamic forces. For the structural model, ANSYS Mechanical (static structural) [13] is used to determine stress and deformation of the weir body under steady hydrodynamic loads. The free surface of the water phase is tracked by using the volume of fluid (VOF) technique in Fluent. In ANSYS Workbench, the FSI analysis can be performed by connecting the ANSYS Fluent with ANSYS Mechanical. Figure (1) illustrates the work flow of a FSI simulation. Here, Fluent iterates until convergence is attained and transfers the pre-requested information (fluid forces) to ANSYS Mechanical, so that this solver begins work to get nodal displacements and stresses [17].

From the designed data of weirs in Fayoum region including the designed dimensions and discharges, it was found that most of weirs in Fayoum region have width ranges from 2m to 10m and height ranges from 1m to 2m. Hence, nine 3D-models, that represent the different weirs / bottom openings configurations prevalent in Fayoum region, have been developed using ANSYS Fluent and ANSYS Mechanical. A definition sketch of the used models is shown in figure (2) and table (1). Simulations were conducted for various ranges of weir heights P, opening diameters D, and discharge Q as presented in table (1).

Table 1. Variables used in the study

Parameter	Symbol	Value	Range		Units
			From	To	
Height of weir	P	1, 1.50 , 2.0	1	2	m
Width of weir	W	3.0, 6.0, 9.0	3	9	m
Diameter of pipe	d	0.25 P, 0.50 P, 0.75 P	4.5	7.0	m
Discharge	Q	varied	0.6	24.3	m^3/s

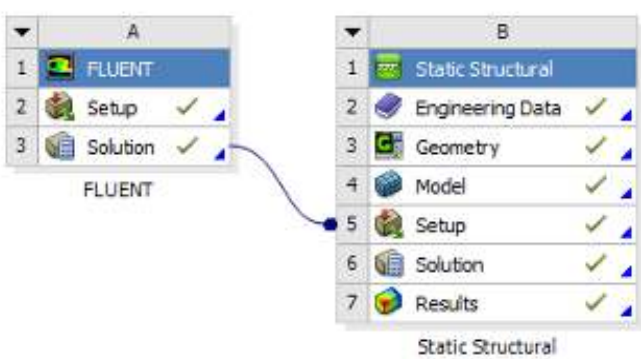


Fig. 1. Coupling Fluent and ANSYS mechanical in ANSYS workbench

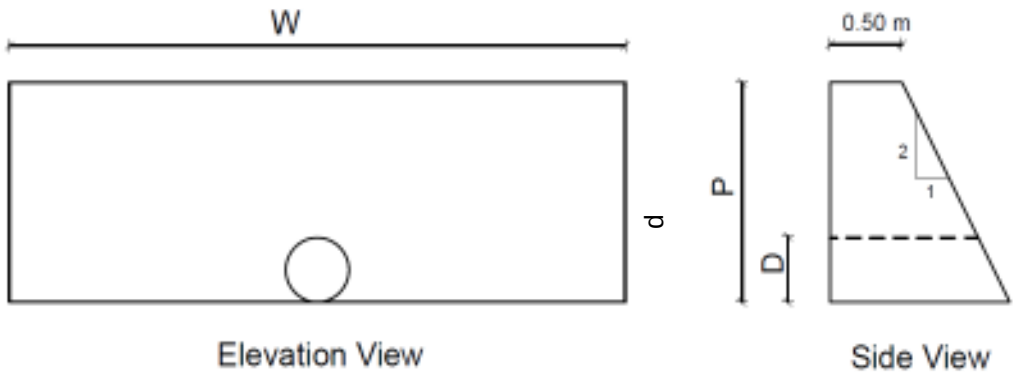


Fig. 2. Definition sketch for the used models

In Fluid Model, ANSYS Fluent is prepared to work using pressure based solver with first order implicit time-steeping formulation which is sufficient for most problems. The 2nd order implicit formulation are used for more accuracy, but it was found that using it takes longer time and negligibly affects the resulted pressure forces. So use of 1st order implicit simulation is sufficient. The solver is configured to use the Green-Gauss Cell-Based theorem to evaluate the gradients and derivatives which are needed to discretize the convection and diffusion terms in the flow conservation equations [19]. The Volume of Fluid multi-phase model with implicit scheme is used and adjusted to simulate open channel flow. The Volume of Fluid model comprises two phases, gas (air) and liquid (water). The densities of air and water were taken to be 1.225 and 1000 kg/m^3, respectively. The dynamic viscosities for air and water were taken to be 1.789E-5 and 1.003E-3, respectively [20]. The standard k-ε turbulence model is used because of its robustness and reasonable accuracy. In the derivation of the k-ε model, the assumption is that the flow is fully turbulent, and the effects of molecular viscosity are negligible. Hence, the standard k-ε model is therefore valid for fully turbulent flows [19]. There are many other turbulence models that can be used such as Spalart-Allmaras, k-Ω and Reynolds Stress model, but it was found that the use of any of them negligibly affect the resulted hydrodynamic forces on the weir body. The fluid domain is made as parallelogram prism in which the weir body is placed inside. It was drawn and defined as fluid volume and the weir body was drawn and defined as the solid volume. Meshes are gradually increased in size from 0.05 to 0.20m by 5% rate of growth, as shown in figure (3). The sides and the bottom of the fluid domain and the surfaces of the weir body were justified to no slip walls.

The main challenges faced during the CFD modeling was the instability of the model related to the choice of the turbulence model and the proper simulation of the open channel flow to permit getting relatively smooth VOF correctly representing the gas / liquid interface. The above mentioned modeling choice enabled the authors to resolve the instability and the interface problems.

For the Structural Model, in ANSYS Mechanical, the geometry was imported so as to use the same geometry as the one used in the Fluid Model. The computational mesh for the weir body was divided using the curvature size function with fine relevance center, high smoothing, slow transition and fine span angles, as shown in figure (4). The sides and the bottom of the weir were set to be fixed supports. The finite element SOLID65 is used for modeling of concrete. The element is defined by eight nodes having three degrees of freedom at each node. The concrete element, SOLID65, is similar to a 3-D structural solid element, SOLID45, but with the addition of special cracking and crushing capabilities. The sizing properties were adjusted to be highly smoothing with slow transition to increase the solution accuracy [13]. The material used in the simulation of the weir body was plain

concrete with characteristic strength F_{cu} = 25 N/mm^2. Young's Modulus was taken to be 2.2E+10 Pa and Poisson's ratio 0.20 [18].

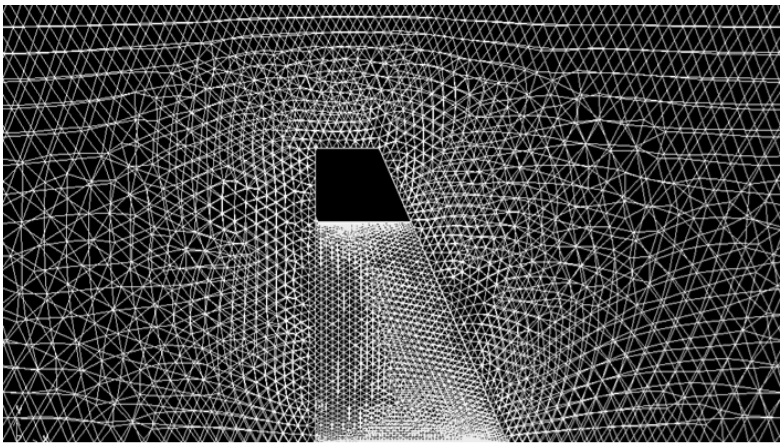


Fig. 3. Sectional side view for the computational meshes of the fluid domain.

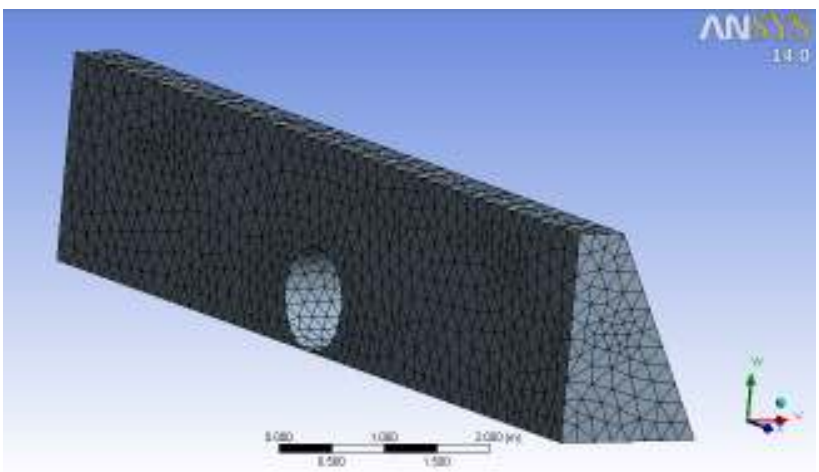


Fig. 4. The computational meshes of the structural model.

3. MODEL VALIDATION

The validation of the hydraulic modeling of a weir with bottom openings using Computational Fluid Dynamics techniques was undertaken by comparing the hydraulic characteristics resulting from the simulation by ANSYS Fluent with the corresponding results from an experimental study undertaken by Mohamed et al. [6]. The upstream water depths resulting from the Fluent models, ($Y_{calculated}$), versus the corresponding experimental ones, ($Y_{measured}$), are plotted in figure (5). It could be noticed that there is a clear agreement between results which means that using ANSYS Fluent in modeling weirs with bottom openings is acceptable.

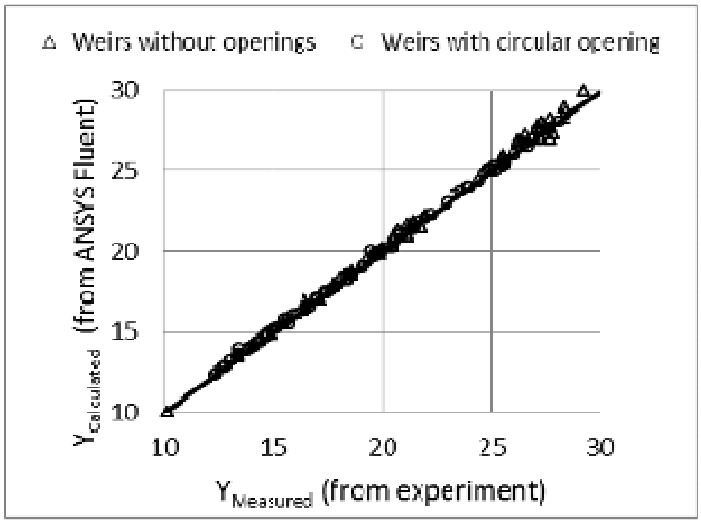


Fig. 5. Model validation (comparison between experimental and numerical results)

4. RESULTS AND DISCUSSION

Using FSI simulation, one could connect the hydraulic characteristics of flow over weirs with one circular bottom opening to the structural analysis and mechanics of the weir body taking into account the hydrodynamic effects. For each model, the changes of water surface profile due to changes in discharge could be obtained as shown in figure (6). Furthermore, the deformations and stresses of the weir body could be obtained as shown in figure (7) and figure (8). For each case, the maximum tensile, the maximum compressive, the maximum shear stresses and the maximum deformation could be obtained. Results of all cases were statistically analyzed using SPSS to find out the correlation between geometry of the weir, the flow characteristics and the generated stresses on the weir body.

It could be found that the maximum tensile stress, σ_{max}, on weir body is directly proportional to the discharge passing through the weir, as shown in figure (9) for the case of a pipe diameter of 0.25, 0.5 and 0.75 of the weir height. Moreover, there is a clear impact of the diameter of the bottom opening on the value of the maximum tensile stress. When the diameter of the bottom opening was 25% of the height of the weir (d=0.25P), the max tensile stress, σ_{max}, increased from 2×10^5 Pa when the discharge Q = 0.6 m^3/s to be 6.3×10^5 Pa when discharge Q = 24.3 m^3/s. When the diameter of the bottom opening was 50% the height of the weir (d=0.50P), the max tensile stress increased, σ_{max}, from 1.3×10^5 Pa when Q = 0.6 m^3/s to be 5.6×10^5 Pa when Q = 24.3 m^3/s. For d=0.75P, the max tensile stress increased from 0.85×10^5 Pa when Q = 0.6 m^3/s to be 3.9×10^5 Pa when Q = 24.3 m^3/s.

For the maximum shear stress, τ_{max}, it could be noticed that the maximum values of shear stress is directly proportional to the discharge passing through the weir and inversely proportional to the diameter of the bottom openings, as shown in figure (10). When the bottom opening diameter was 25% of the height of the weir (d=0.25P), the max shear stress, τ_{max}, increased from 10×10^4 Pa when Q = 0.6 m^3/s to be 25.8×10^4 Pa when Q = 24.3 m^3/s. When the bottom opening diameter was 50% of the height of the weir (d=0.50P), the max shear stress, τ_{max}, increased from 6×10^4 Pa when Q = 0.6 m^3/s to be 25×10^4 when Q = 24.3 m^3/s. When the bottom opening diameter was 75% of the height of the weir (d=0.75P), the max shear stress increased from 4×10^4 Pa when Q = 0.6 m^3/s to be 17×10^4 Pa when Q = 24.3 m^3/s.

The relation between maximum compression stresses, σ_{min}, on the weir body against the passing discharge is presented in figure (11). The maximum compression stress is directly

proportional to the discharge and inversely proportional to the bottom opening diameter. When the bottom opening diameter was 25% of the weir height (d=0.25P), the max compression stress, σ_{min}, changed from -1×10^5 Pa when Q = 0.6 m^3/s to -3.9×10^5 Pa when Q = 24.3 m^3/s. When the bottom opening diameter was 50% of the weir height (d=0.50P), the max compression stress, σ_{min}, changed from -0.85×10^5 Pa when Q = 0.6 m^3/s to -3.5×10^5 Pa when Q = 24.3 m^3/s. When the bottom opening diameter was 75% of the weir height (d=0.75P), the max compression stress , σ_{min}, changed from -0.5×10^5 Pa when Q = 0.6 m^3/s to -2.7×10^5 Pa when Q = 24.3 m^3/s.

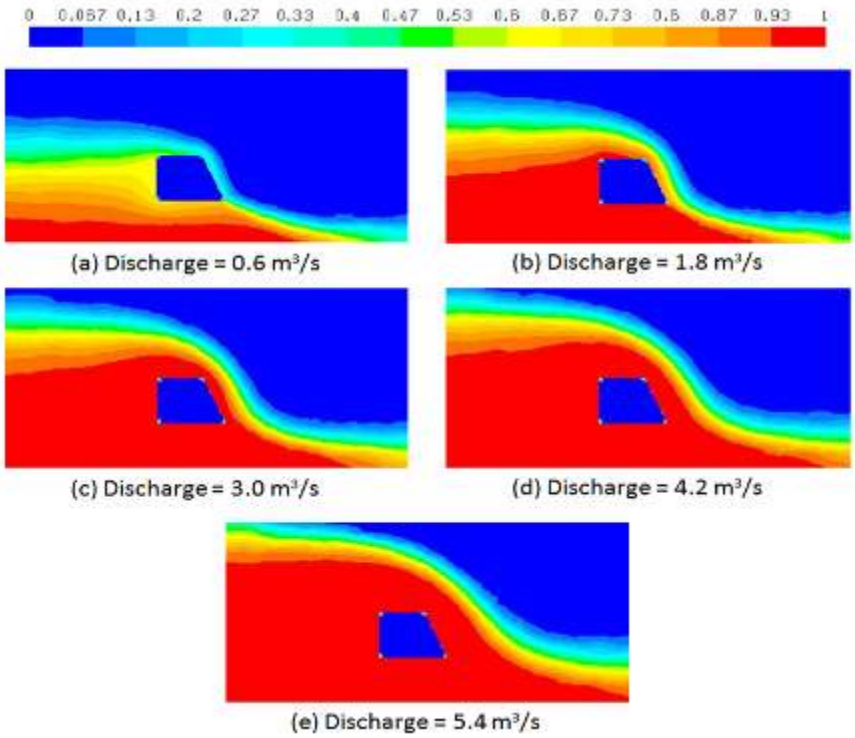


Fig. 6. Example of contours of Volume Fraction (water) [Width (w) = 3m, height (p) = 1m, pipe diameter (d) = 0.5 m]

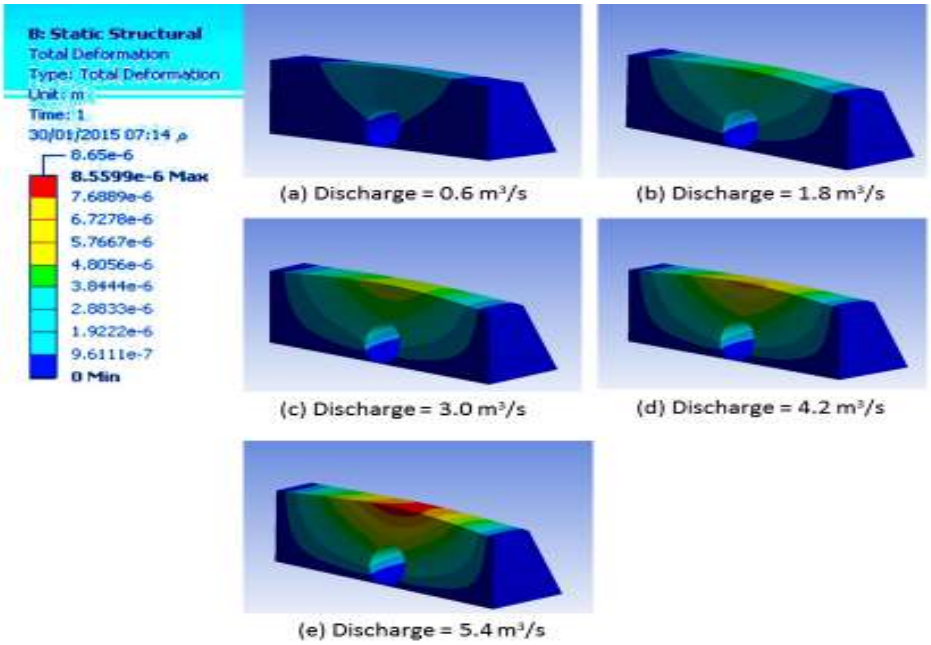


Fig. 7. Example of total deformation of the weir due to change in discharge [Width (w) = 3m, height (p) = 1m, pipe diameter (d) = 0.5 m]

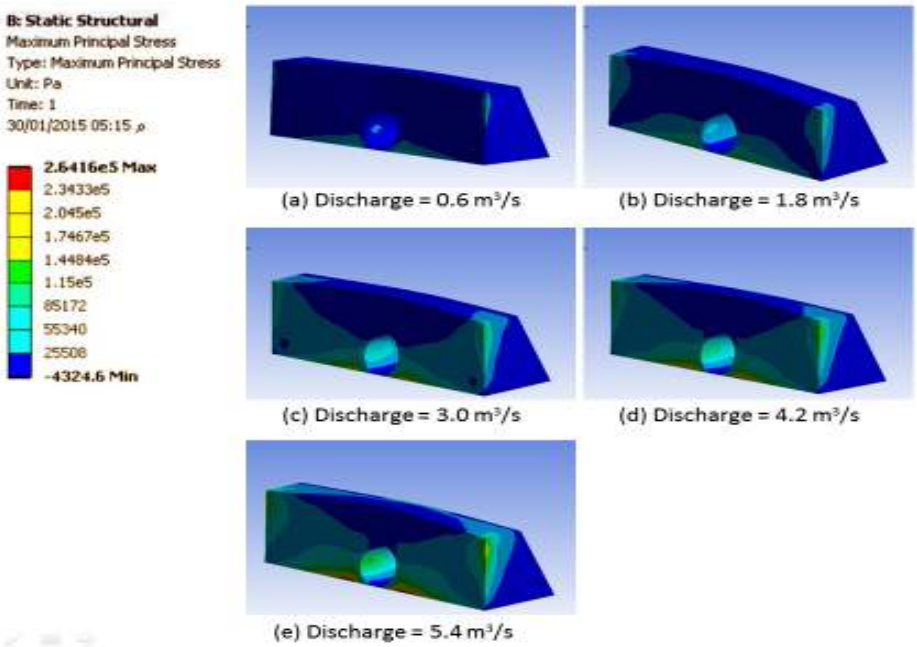


Fig. 8. Example of maximum tensile stress in the weir due to change in discharge [Width (w) = 3m, height (p) = 1m, pipe diameter (d) = 0.5 m]

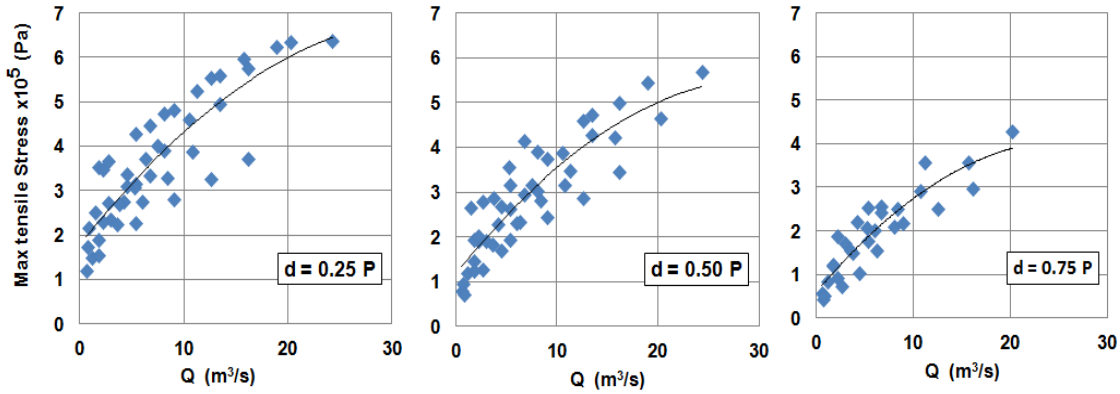


Fig. 9. Relationships between maximum tensile stress, σ_{max}, on weir body and passing discharge for different bottom outlet diameter to depth of weir ratios

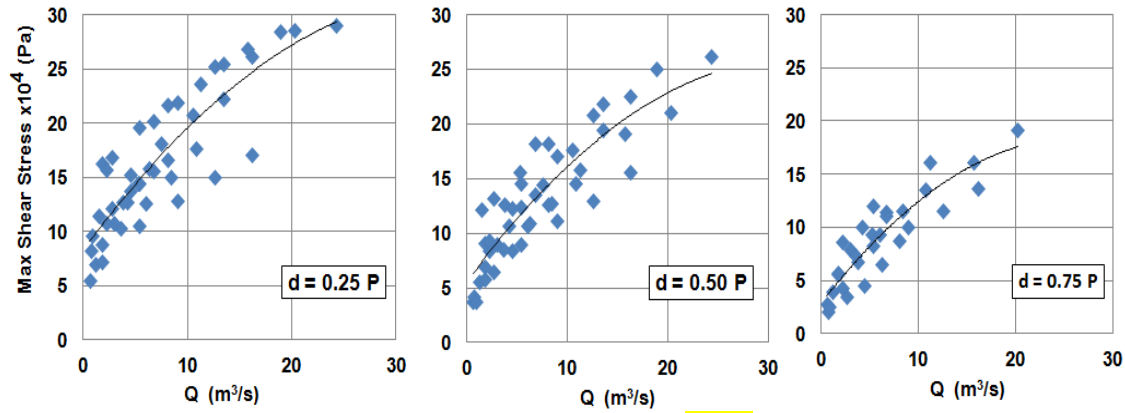


Fig. 10. Relationships between maximum shear stress, τ_{max}, on weir body and passing discharge for different bottom outlet diameter to depth of weir ratios

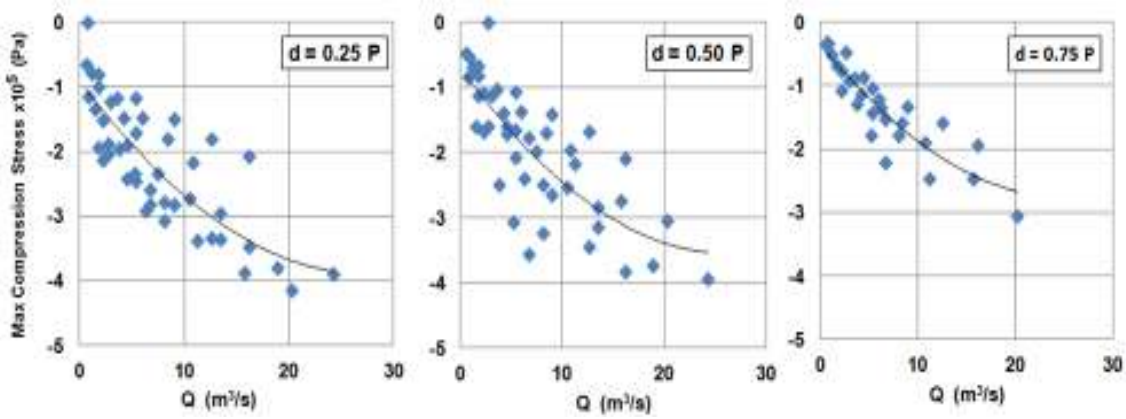


Fig. 11. Relationships between maximum compression stresses, σ_{min}, and passing discharge for different bottom outlet diameter to depth of weir ratios

A relation between the maximum shear stress, τ_{max}, (in Pa) and the maximum tensile stress, σ_{max}, (in Pa) could be plotted, as shown in figure (12) and expressed as follows:

$$\tau_{max} = 0.45\ \sigma_{max} + 2728.83 \qquad \text{..... (1)}$$

Moreover, there is a relation between the maximum deformation, δ_{max}, (in meters) and the maximum tensile stress, σ_{max}, (in Pa) which could be expressed as follows:

$$\delta_{max} = (6.78 \times 10^{-11})\ \sigma_{max} + 1.02\times10^{-5} \qquad \text{..... (2)}$$

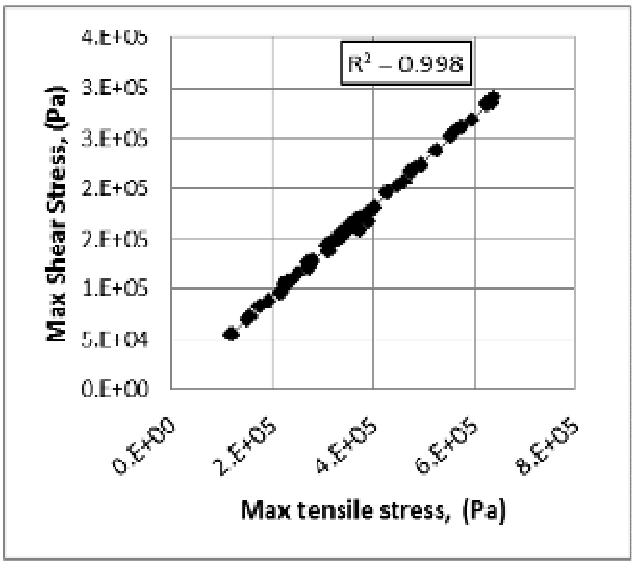


Fig. 12. Relationship between maximum shear stress, τ_{max}, with max tensile stress, σ_{max}, on weir body

4.1. Statistical analysis

Statistical analysis was undertaken to assess the above mentioned descriptive findings and to develop relationships that could be used by designers without carrying out tedious modeling exercises. The correlation coefficients (r) between dependent variables of interest and their predictors (or independent variables) are shown in tables (2) to (4), along with the number of available data points or results (n) and the probability value (p-value) for which the correlation coefficient is statistically significant. It was found that there is a statistically significant positive correlation with probability value, (p-value < 0.001) between maximum tensile stress, σ_{max}, and the weir height P, the weir width W and the discharge Q, while as there is a statistically significant negative correlation with the pipe diameter d as illustrated in table (2).

For the maximum compression stress, σ_{min}, it was found that there is a statistically significant negative correlation (with p-value <0.001) between the maximum compression stress, σ_{min}, and the weir height P, the weir width W and the discharge Q and there is no statistically significant correlation with pipe diameter d, as shown in table (3).

Table 2. Correlation between max tensile stresses and other variables

Variables (n=120)	Max. tensile stress, σ_{max}, (Pa)	
	r	p-value
Height, P (m)	0.38	<0.001
Width, W (m)	0.46	<0.001
Diameter, d (m)	-0.24	0.009
Discharge, Q (m^3/s)	0.80	<0.001

Table 3. Correlation between max compression stresses and other variables

Variables (n=120)	Max. compression stress, σ_{min}, (Pa)	
	r	p-value
Height, P (m)	-0.51	<0.001
Width, W (m)	-0.30	0.001
Diameter, d (m)	0.069	0.5
Discharge, Q (m^3/s)	-0.78	<0.001

For the maximum shear stress, τ_{max}, there is a statistically significant positive correlation (with p-value <0.001) between max shear stress τ_{max}, and weir height P, weir width w, and discharge Q and a statistically negative correlation with pipe diameter d, as illustrated in table (4). As shown in table (5), there is a statistically significant positive correlation (with p-value <0.001) between the maximum deformation, δ_{max}, in the weir body and weir height P, weir width w, and discharge Q.

Table 4. Correlation between max shear stress and other variables

Variables (n=120)	Max. shear Stress (Pa)	
	r	p-value
Height, P (m)	0.37	<0.001
Width, W (m)	0.47	<0.001
Diameter, d (m)	-0.25	0.007
Discharge, Q (m^3/s)	0.80	<0.001

Table 5. Correlation between total deformation and other variables

Variables (n=120)	Max. deformation (m)	
	r	p-value
Height, P (m)	0.55	<0.001
Width, W (m)	0.46	<0.001
Diameter, d (m)	0.15	0.1
Discharge, Q (m^3/s)	0.76	<0.001

As there is statistical significance between the maximum tensile stress and other variables a multivariate regression analysis could be applied. The effect of each different variable on the prediction of maximum tensile stress was shown in table (6). There are many different types of statistical techniques which could be applied. The multivariate regression is the most common and straight forward technique, since the relationships are fairly linear. It attempts to develop an equation that can describe how elements in a vector of variables respond simultaneously to changes in others. The multivariate regression analysis could be applied to predict the maximum deformation, δ_{max}, occurred on the weir body as shown in table (7). The maximum tensile stress, σ_{max}, (in Pa) and the maximum deformation, δ_{max}, (in meters) could be predicted from the following equations:

$$\sigma_{max} \text{ (predicted)} = 64185.194+158644.89\,(P) -201007.158\,(d) +18328.98\,(Q) \quad \text{..... (3)}$$

$$\delta_{max} \text{ (predicted)} = -1.572E\text{-}5+1.182E\text{-}5(P) +7.187E\text{-}7(w) +1.098E\text{-}6(Q) \quad \text{..... (4)}$$

Table 6. Stepwise multi-linear regression analysis model to determine predictors for Maximum tensile stress (Pa)

Variables	Constant	Sig.
Constant	64185.194	-----
Height of weir, P (m)	158644.89	<0.001
Width of weir, W (m)	0.054	0.7
Diameter of pipe, d (m)	-201007.16	<0.001
Discharge, Q (m^3/s)	18328.98	<0.001

Table 7. Stepwise multi-linear regression analysis model to determine predictors for Maximum deformation (m)

Variables	Constant	Sig.
Constant	-1.572E-5	-----
Height of weir, P (m)	1.182E-5	<0.001
Width of weir, W (m)	7.187E-7	<0.001
Diameter of pipe, d (m)	-0.058	0.2
Discharge, Q (m^3/s)	1.098E-6	<0.001

On the other hand, a statistically significant relationship exists between maximum shear stress, τ_{max}, (in Pa) and other variables. Moreover, a statistically significant relationship exists also between maximum compression stress, σ_{min}, (in Pa) and other variables. The relationships are shown by equations (5) and (6) and the statistical significance of the independent variables of each equation is tabulated in table (8) and table (9).

$$\tau_{max} \text{ (predicted)} = 32253.09 + 70847.206(P) - 91546.76(d) + 8244.068(Q) \quad \text{..... (5)}$$

$$\sigma_{min} \text{ (predicted)} = -1691.552 -117359.744\,(P) + 95413.934\,(d) -12786.426\,(Q) + 4290.747(w) \quad \text{..... (6)}$$

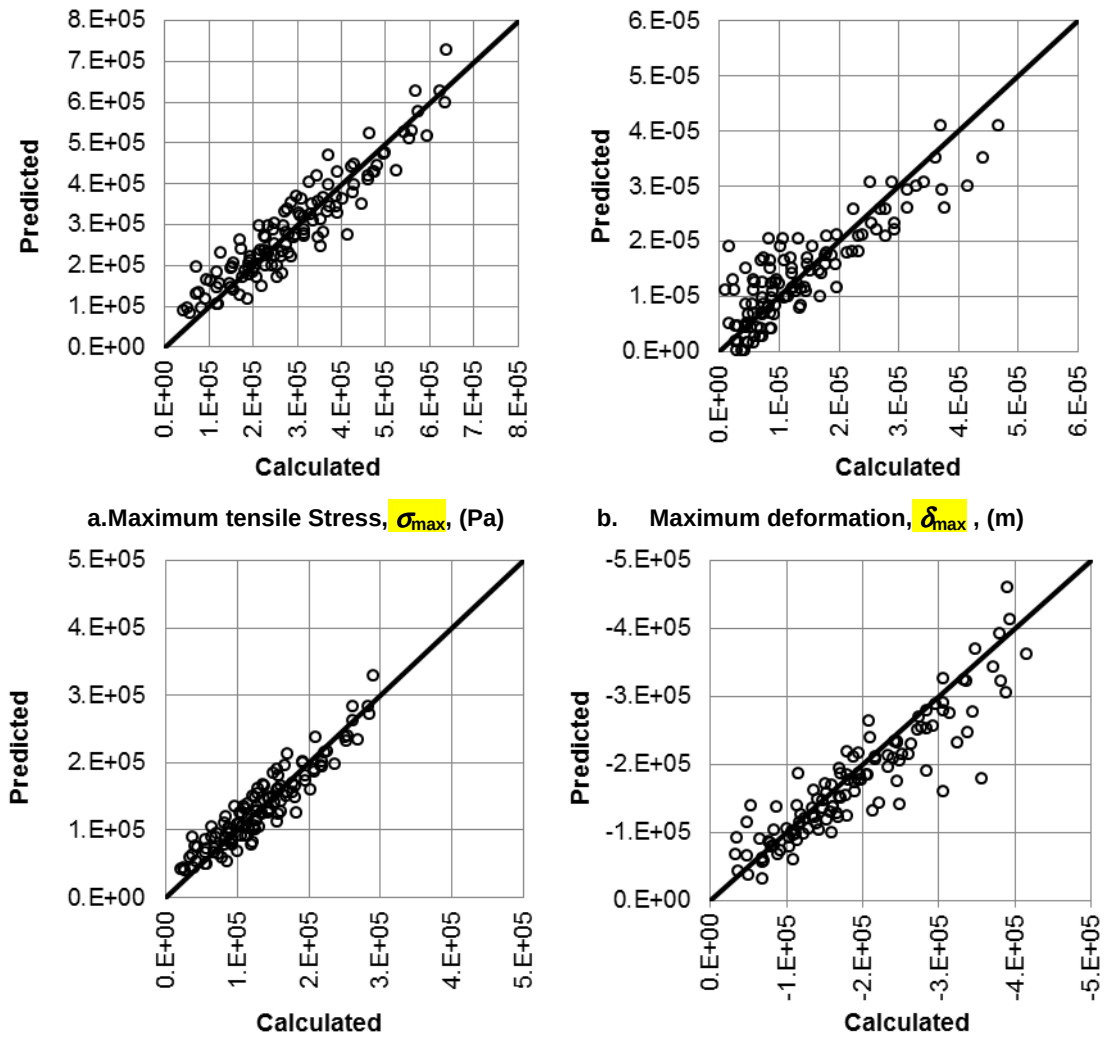
Table 8. Stepwise multi-linear regression analysis model to determine predictors for Maximum shear stress (Pa)

Variables	Constant	Sig.
Constant	32253.09	-----
Height of weir, P (m)	70847.21	<0.001
Width of weir, W (m)	0.068	0.09
Diameter of pipe, d (m)	-91546.76	<0.001
Discharge, Q (m^3/s)	8244.07	<0.001

Table 9. Stepwise multi-linear regression analysis model to determine predictors for Maximum compression stress (Pa)

Variables	Constant	Sig.
Constant	-1691.55	___
Height of weir, P (m)	-117359.74	<0.001
Width of weir, W (m)	4290.747	0.02
Diameter of pipe, d (m)	95413.93	<0.001
Discharge, Q (m^3/s)	-12786.43	<0.001

A comparison between the predicted and the calculated values for maximum tensile stress, maximum deformation, maximum shear stress and maximum compression stress was undertaken to represent the quality of prediction. It could be found that the predicted values are close to the corresponding calculated values, as shown in figure (13).



a.Maximum tensile Stress, σ_{max}, (Pa)

b. Maximum deformation, δ_{max} , (m)

c.Maximum shear Stress, τ_{max}, (Pa)

d. Maximum compression stress, σ_{min}, (Pa)

Fig. 13. Relationship between predicted and calculated maximum stresses and deformation on weir body

5. CONCLUSIONS

From the above investigations, the following conclusions were reached:

- Modification of Fayoum type weirs by making a bottom circular opening affects the structural behavior of the weir.
- The discharge, the diameter of opening and the dimensions of weir affect the stresses generated in the weir body.
- Two relationships were developed between the resulting maximum deformation and the maximum tensile stress and between the resulting maximum stresses among themselves. The first relationship is between the maximum tensile stress, σ_{max}, and the maximum deformation, δ_{max}, and the second relationship is between the maximum shear stress, τ_{max}, and the maximum tensile stress, σ_{max}.
- Four other formulae were developed to estimate the values of the maximum tensile stress, the maximum shear stress, the maximum compression stress and the maximum deformation for the weir width ranges from 3 to 9 m, the weir height ranges from 1 to 2 m and the diameter of opening from 0.25 to 0.75 of weir height.
- The Maximum deformations, $\boldsymbol{\delta_{max}}$, of the weir body is very small and can be considered as unaffected by the incorporation of openings.
- In selecting the opening diameter needed to increase the passing discharge through the channel, the stress should be estimated and compared with the allowable stresses to avoid collapsing and to know the required strengthening mitigation.
- For further studies, the structural behavior of weirs with more than one pipe or with other shape of openings needs also to be studied. Also many other types of weir which are widely used around the world can be studied for similar cases.

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