

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 existing weirs along canals. In canals with weir systems, it will be very costly to reconstruct the weirs along the canals. That gives great importance to study the possibility of making openings in weirs to increase the discharge passing through them.

Aims: This research studies the structural behavior of rectangular weirs with one bottom circular opening at their middle. Making an opening in the weir changes the hydraulic characteristics and the hydrodynamic forces which lead to changing the structural behavior of the weir.

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, maximum compression stress, maximum shear stress and maximum deformation occurring on weir body.

Results: There are clear correlations between stresses on the weir, including maximum tensile stress, maximum shear stress and maximum compression stress, and dimensions of the weir and its opening diameter. Hence, the multiple regression analysis was applied to predict the maximum stresses and the total 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 compression stress, and maximum deformation around circular openings in Fayoum type weirs. By comparing 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]

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 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. In canals with weir systems, it will be very costly to reconstruct the weirs along the 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 estimate the maximum tensile, the maximum compressive, the maximum shear stresses and the total deformation due to this opening. 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. Numerical simulations are less expensive and do not need laboratory equipment. FSI simulations are 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

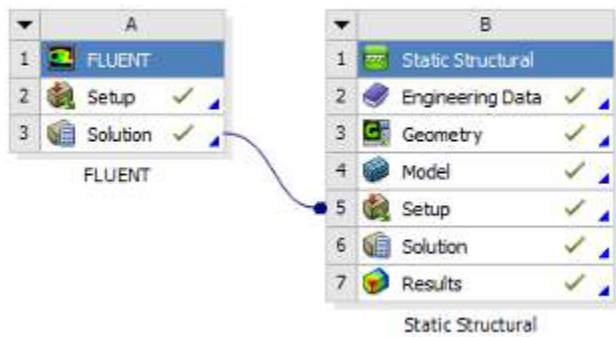
In this research, the FSI analysis has been conducted on a standard Fayoum weir with one bottom circular opening. The fluid and structural models have been created with appropriate dimensions. For the hydraulic model, ANSYS Fluent [13] is used to simulate the flow through the weir taking into account 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

65 Workbench, the FSI analysis can be performed by connecting the ANSYS Fluent with
 66 ANSYS Mechanical. Figure (1) illustrates the work flow of a FSI simulation. Here, Fluent
 67 iterates until convergence is attained and transfers the pre-requested information (fluid
 68 forces) to ANSYS Mechanical, so that this solver begins work to get nodal displacements
 69 and stresses [17].

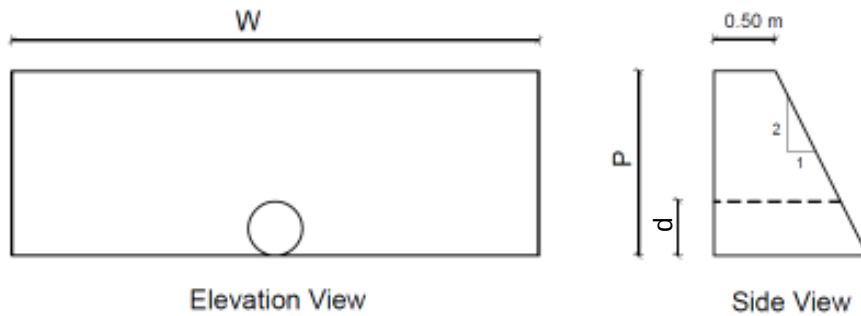
70 Nine models, that represent the different weirs / bottom openings configurations prevalent in
 71 Fayoum region, have been developed using ANSYS Fluent and ANSYS Mechanical. A
 72 definition sketch of the used models is shown in figure (2) and table (1). Simulations were
 73 conducted for various ranges of weir heights P, opening diameters D, and discharge Q as
 74 presented in table (1).

75
 76 **Table 1. Variables used in the study**
 77

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



78
 79 **Fig. 1. Coupling Fluent and ANSYS mechanical in ANSYS workbench**



80
 81 **Fig. 2. Definition sketch for the used models**
 82

83 The fluid model comprises two phases, gas (air) and liquid (water). The densities of air and
 84 water were taken to be 1.225 and 1000 kg/m³, respectively. The dynamic viscosities for air
 85 and water were taken to be 1.789E-5 and 1.003E-3, respectively. The material used in
 86 simulation of the weir body was plain concrete with characteristic strength $F_{cu} = 25 \text{ N/mm}^2$.
 87 Young's Modulus was taken to be 2.2E+10 Pa and Poisson's ratio 0.20 [18].

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 depth resulting from the Fluent models and the experimental models are plotted in figure (3). 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.

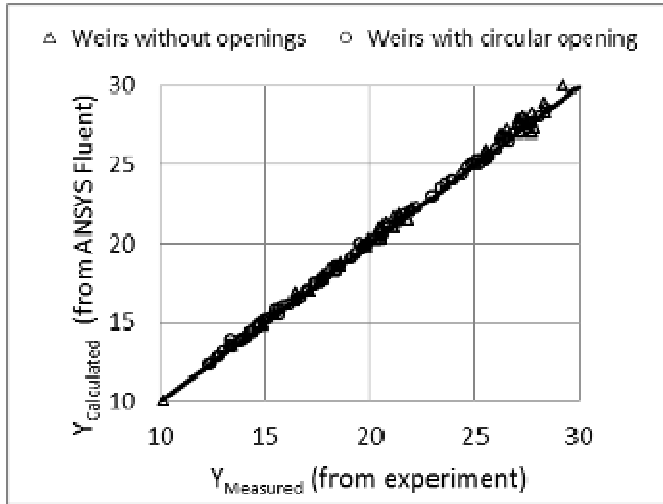


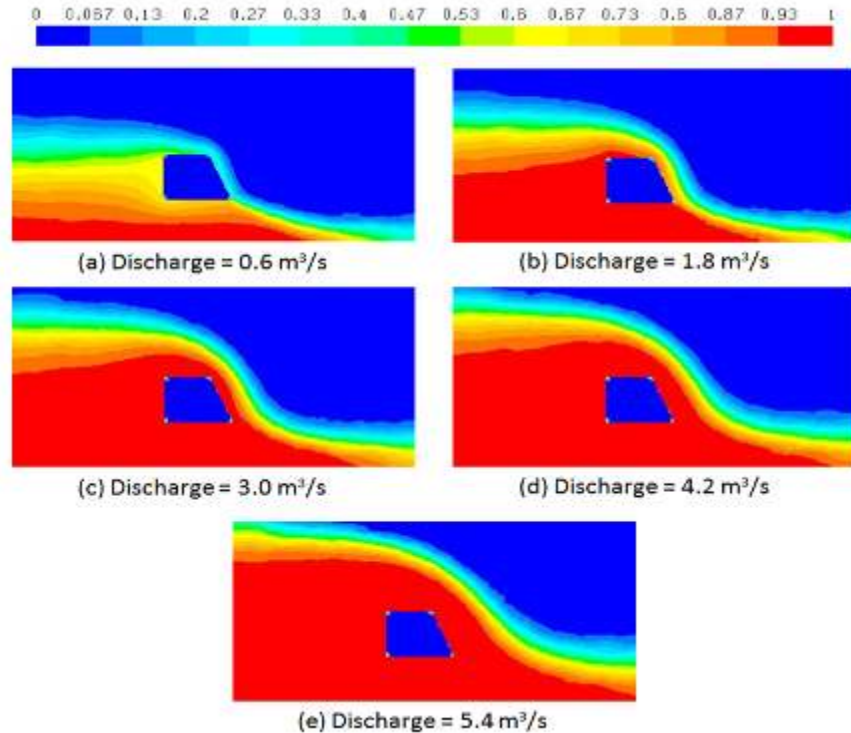
Fig. 3. Model validation (comparison between experimental and numerical results)

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 (4). Furthermore, the deformations and stresses of the weir body could be obtained as shown in figure (5) and figure (6). For each case, the maximum tensile, the maximum compressive, the maximum shear stresses and the total 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 on weir body is directly proportional to the discharge passing through the weir, as shown in figure (7) 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 increased from 2×10^5 Pa when the discharge $Q = 0.6 \text{ m}^3/\text{s}$ to be 6.3×10^5 Pa when discharge $Q = 24.3 \text{ m}^3/\text{s}$. When the diameter of the bottom opening was 50% the height of the weir ($d=0.50P$), the max tensile stress increased from 1.3×10^5 Pa when $Q = 0.6 \text{ m}^3/\text{s}$ to be 5.6×10^5 Pa when $Q = 24.3 \text{ m}^3/\text{s}$. For $d=0.75P$, the max tensile stress increased from 0.85×10^5 Pa when $Q = 0.6 \text{ m}^3/\text{s}$ to be 3.9×10^5 Pa when $Q = 24.3 \text{ m}^3/\text{s}$.

125 For the maximum shear stress, it could be noticed that the maximum values of shear stress
 126 is directly proportional to the discharge passing through the weir and inversely proportional
 127 to the diameter of the bottom openings, as shown in figure (8). When the bottom opening
 128 diameter was 25% of the height of the weir ($d=0.25P$), the max shear stress increased from
 129 10×10^4 Pa when $Q = 0.6 \text{ m}^3/\text{s}$ to be 25.8×10^4 Pa when $Q = 24.3 \text{ m}^3/\text{s}$. When the bottom
 130 opening diameter was 50% of the height of the weir ($d=0.50P$), the max shear stress
 131 increased from 6×10^4 Pa when $Q = 0.6 \text{ m}^3/\text{s}$ to be 25×10^4 when $Q = 24.3 \text{ m}^3/\text{s}$. When the
 132 bottom opening diameter was 75% of the height of the weir ($d=0.75P$), the max shear stress
 133 increased from 4×10^4 Pa when $Q = 0.6 \text{ m}^3/\text{s}$ to be 17×10^4 Pa when $Q = 24.3 \text{ m}^3/\text{s}$.
 134 The relation between maximum compression stresses on the weir body against the passing
 135 discharge is presented in figure (9). The maximum compression stress is directly
 136 proportional to the discharge and inversely proportional to the bottom opening diameter.
 137 When the bottom opening diameter was 25% of the weir height ($d=0.25P$), the max
 138 compression stress increased from -1×10^5 Pa when $Q = 0.6 \text{ m}^3/\text{s}$ to -3.9×10^5 Pa when $Q =$
 139 $24.3 \text{ m}^3/\text{s}$. When the bottom opening diameter was 50% of the weir height ($d=0.50P$), the
 140 max compression stress increased from -0.85×10^5 Pa when $Q = 0.6 \text{ m}^3/\text{s}$ to -3.5×10^5 Pa
 141 when $Q = 24.3 \text{ m}^3/\text{s}$. When the bottom opening diameter was 75% of the weir height
 142 ($d=0.75P$), the max compression stress increased from -0.5×10^5 Pa when $Q = 0.6 \text{ m}^3/\text{s}$ to $-$
 143 2.7×10^5 Pa when $Q = 24.3 \text{ m}^3/\text{s}$.
 144



145
 146 **Fig. 4. Example of contours of Volume Fraction (water) [Width (w) = 3m, height (p) =**
 147 **1m, pipe diameter (d) = 0.5 m]**

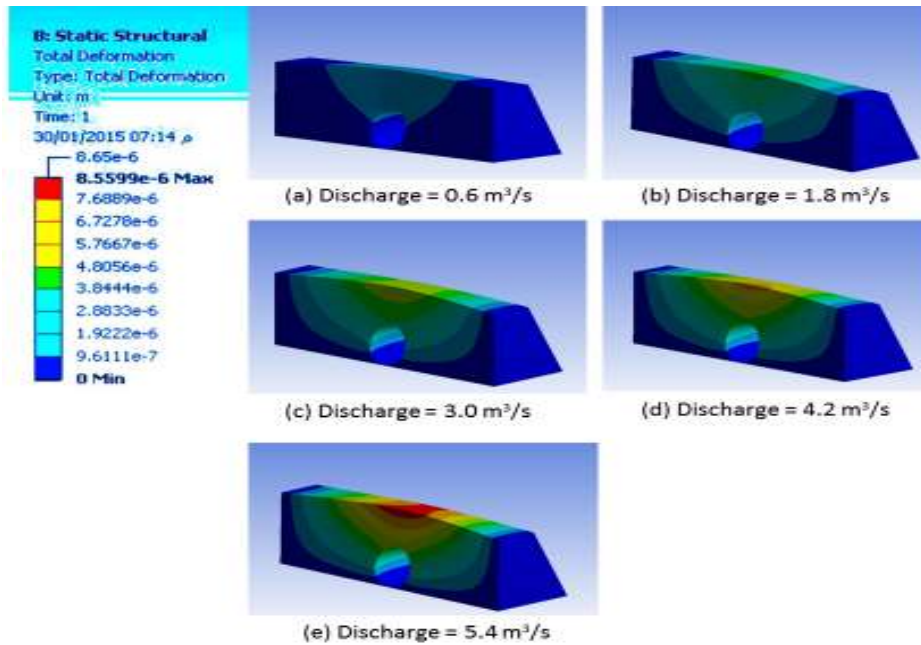


Fig. 5. Example of total deformation of the weir due to change in discharge [Width (w) = 3m, height (p) = 1m, pipe diameter (d) = 0.5 m]

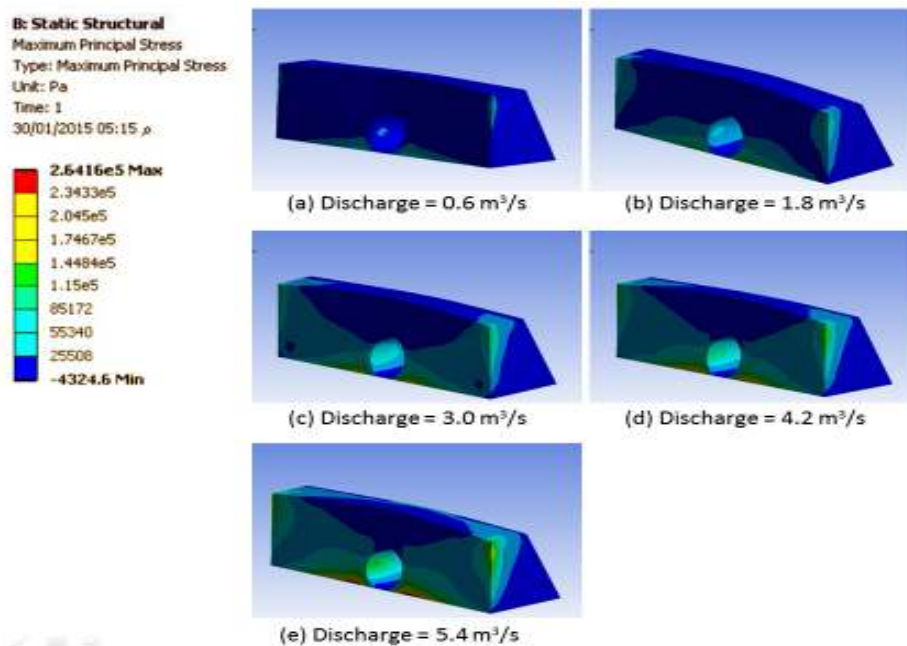
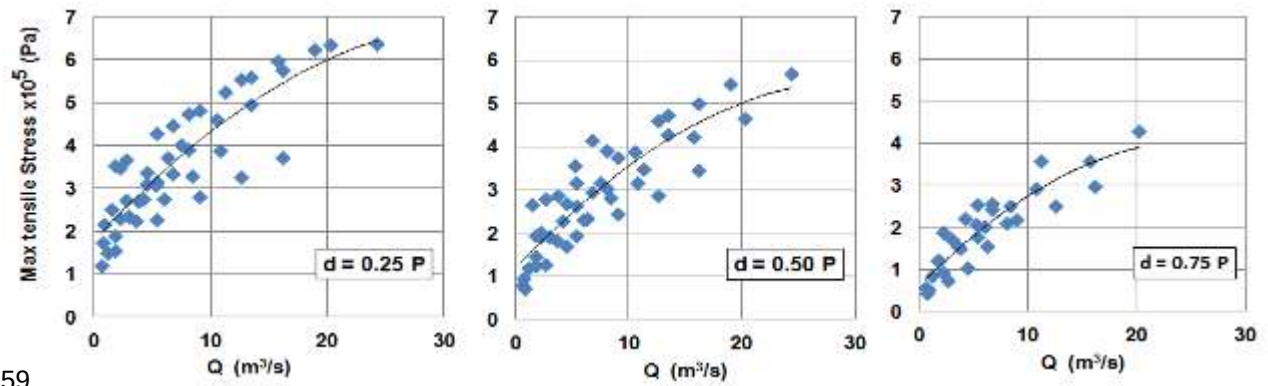
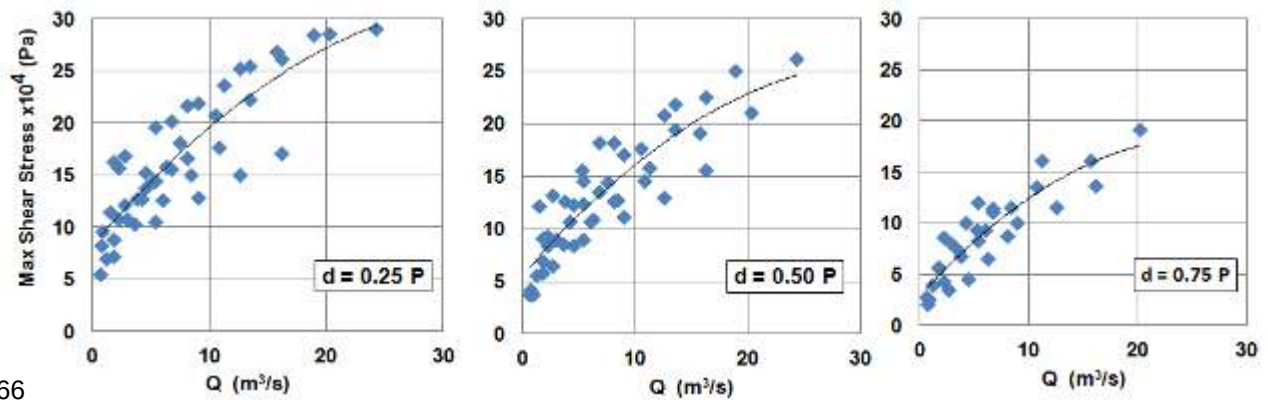


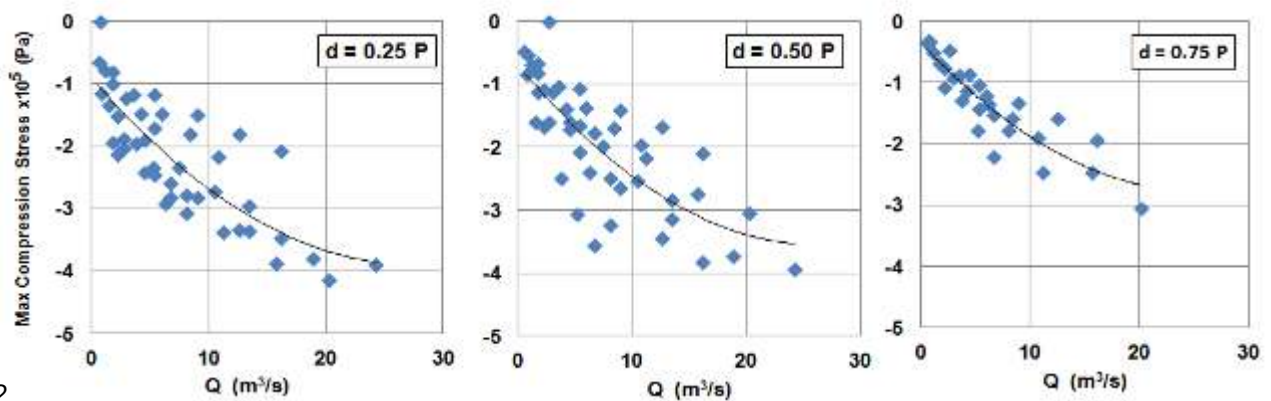
Fig. 6. Example of maximum tensile stress in the weir due to change in discharge [Width (w) = 3m, height (p) = 1m, pipe diameter (d) = 0.5 m]



159
160
161 **Fig. 7. Relationships between maximum tensile stress on weir body and passing**
162 **discharge for different bottom outlet diameter to depth of weir ratios**
163
164
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166
167
168 **Fig. 8. Relationships between maximum shear stress on weir body and passing**
169 **discharge for different bottom outlet diameter to depth of weir ratios**
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172
173 **Fig. 9. Relationships between maximum compression stresses and passing discharge**
174 **for different bottom outlet diameter to depth of weir ratios**
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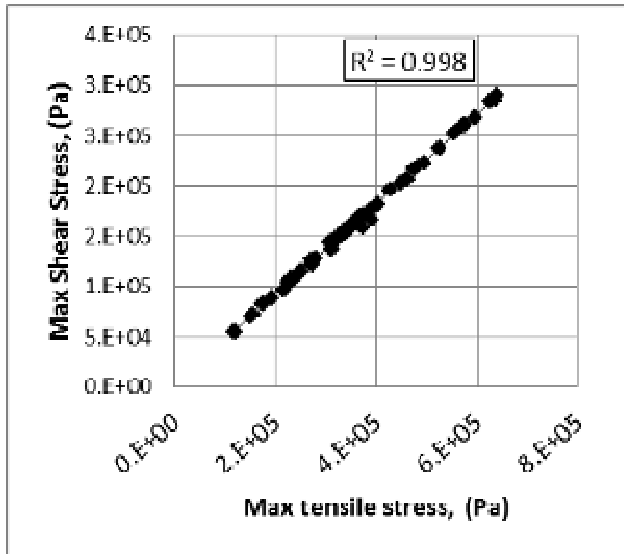
177 A relation between the maximum shear stress (in Pa) and the maximum tensile stress (in
178 Pa) could be plotted, as shown in figure (10) and expressed as follows:

179 **Max shear stress = 0.45 (Max tensile stress) + 2728.83** (1)

180 Moreover, there is a relation between the maximum deformation (in meters) and the
181 maximum tensile stress (in Pa) which could be expressed as follows:

182 **Max deformation = $(6.78 \times 10^{-11}) \times \text{Max tensile stress} + 1.02 \times 10^{-5}$** (2)

183



184

185 **Fig. 10. Relationship** between maximum shear stress with max tensile stress on weir
186 body

187

188

189 4.1. Statistical analysis

190 Statistical analysis was undertaken to assess the above mentioned descriptive findings and
191 to develop relationships that could be used by designers without carrying out tedious
192 modeling exercises. The correlation coefficients (r) between dependent variables of interest
193 and their predictors (or independent variables) are shown in tables (2) to (4), along with the
194 number of available data points or results (n) and the probability value (p-value) for which
195 the correlation coefficient is statistically significant. It was found that there is a statistically
196 significant positive correlation with probability value, (p-value < 0.001) between maximum
197 tensile stress and the weir height P, the weir width W and the discharge Q, while as there is
198 a statistically significant negative correlation with the pipe diameter d as illustrated in table
199 (2). For the maximum compression stress, it was found that there is a statistically significant
200 negative correlation (with p-value < 0.001) between the maximum compression stress and
201 the weir height P, the weir width W and the discharge Q and there is no statistically
202 significant correlation with pipe diameter d, as shown in table (3).

203

204

Table 2. Correlation between max tensile stresses and other variables

Variables (n=120)	Max tensile stress (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 (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, there is a statistically significant positive correlation (with p-value <0.001) between max shear stress 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 Total Deformation 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)	Total 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 total deformation occurred on the weir body as shown in table (7). The maximum tensile stress (in Pa) and the maximum total deformation (in meters) could be predicted from the following equations:

Max tensile stress (predicted) = 64185.194+158644.89 (P) -201007.158 (d) +18328.98 (Q) (3)

231 **Total deformation (predicted) = -1.572E-5+1.182E-5(P) +7.187E-7(w) +1.098E-6(Q) (4)**

232 **Table 6. Stepwise multi-linear regression analysis model to determine predictors for**
 233 **Max 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

234
 235 **Table 7. Stepwise multi-linear regression analysis model to determine predictors for**
 236 **Max total deformation (m)**
 237

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

238
 239 On the other hand, a statistically significant relationship exists between maximum shear
 240 stress (in Pa) and other variables. Moreover, a statistically significant relationship exists also
 241 between maximum compression stress (in Pa) and other variables. The relationships are
 242 shown by equations (5) and (6) and the statistical significance of the independent variables
 243 of each equation is tabulated in table (8) and table (9).

244 **Max shear stress (predicted) = 32253.09 + 70847.206(P) - 91546.76(d) + 8244.068(Q) (5)**

245 **Max compression stress (predicted) = -1691.552 -117359.744 (P) + 95413.934 (d) -12786.426 (Q)**
 246 **+ 4290.747(w) (6)**

247
 248 **Table 8. Stepwise multi-linear regression analysis model to determine predictors for**
 249 **Max shear stress (Pa)**
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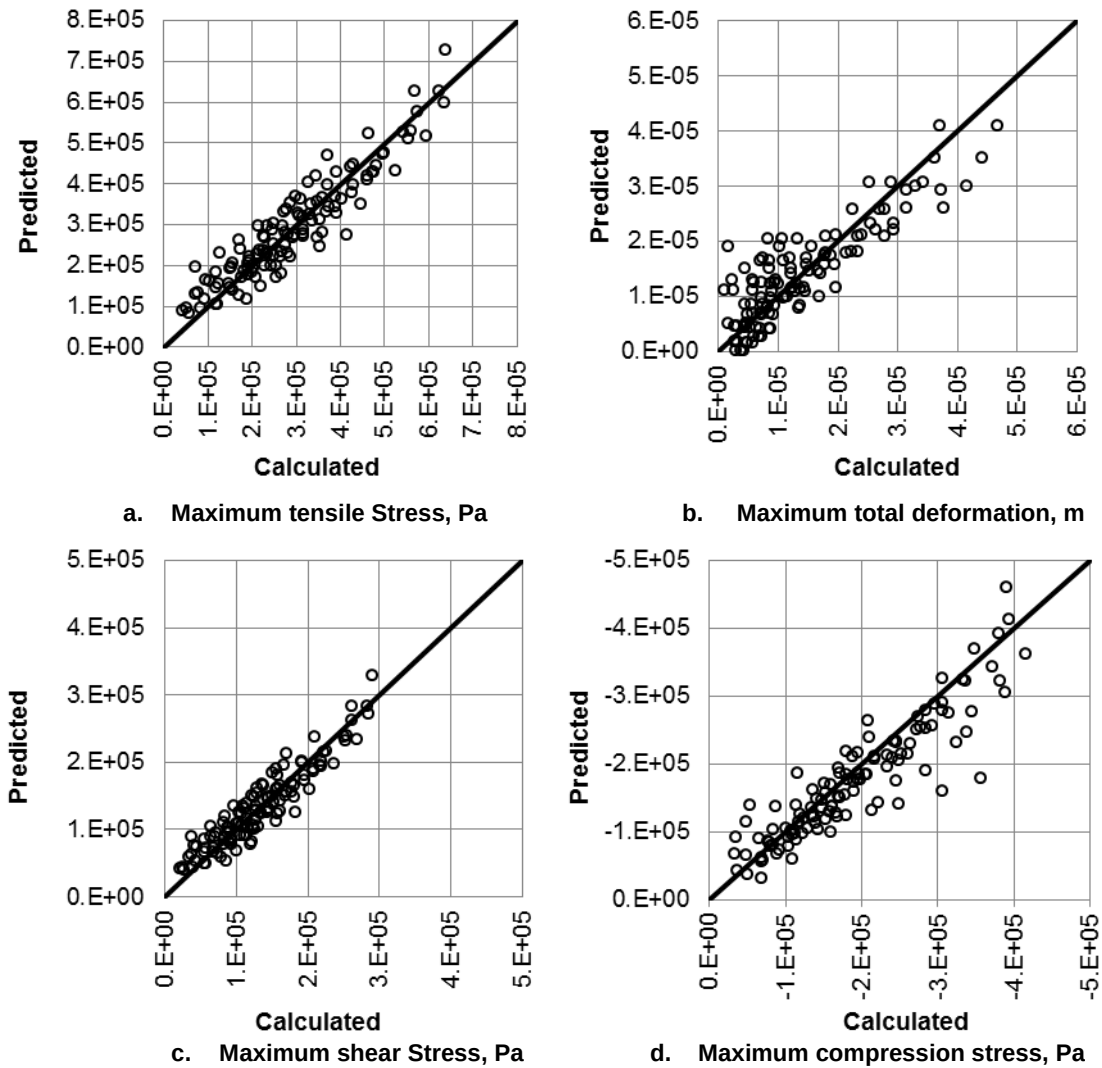
Variables	Constant	Sig.
Constant	32253.09	-----
Height of weir, P (m)	70847.21	<0.001
Width of weir, W (m)	0.068	0.09
Diameter of pipe, d (m)	-91546.76	<0.001
Discharge, Q (m ³ /s)	8244.07	<0.001

251
 252
 253

254 **Table 9. Stepwise multi-linear regression analysis model to determine predictors for**
 255 **Max compression stress (Pa)**
 256

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

257
 258 A comparison between the predicted and the calculated values for maximum tensile stress,
 259 maximum total deformation, maximum shear stress and maximum compression stress was
 260 **undertaken** to represent the quality of prediction. It could be found that the predicted values
 261 are close to the corresponding calculated values, as shown in figure (12).
 262



263 **Fig. 12. Relationship** between predicted and calculated maximum stresses and
 264 **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.
- Four 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 range from 3 to 9 m, the weir height range from 1 to 2 m and the diameter of opening from 0.25 to 0.75 of weir height.
- 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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