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A Control Program for Hydropower Operation Based on Minimizing the Principal Stress Values on the Dam Body: Mosul Dam Case Study

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ABSTRACT

This study examines the vibrations produced by hydropower operations to improve embankment dam safety. This study consists of two parts: In the first part, ANSYS-CFX was used to generate a three-dimensional (3-D) finite volume (FV) model to simulate a vertical Francis turbine unit in the Mosul hydropower plant. The pressure pattern result of the turbine model was transformed into the dam body to show how the turbine unit's operation affects the dam's stability. The upstream reservoir conditions, various flow rates, and fully open inlet gates were considered. In the second part of this study, a 3-D FE Mosul dam model was simulated using an ANSYS program. The operational turbine model's water pressure pattern is conveyed to the dam's turbine-shared zone. The maximal and minimal upstream reservoir water levels were investigated. A control program was created depending on the principle stress model results collected from the operation of the hydropower plant with the minimum principal stress on the dam body. This research suggests an enhanced turbine operating system, reducing stress on the dam body and increasing dam operation life.

Keywords: Francis Turbine, ANSYS, Principal Stress, Mosul Dam.

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برنامج تحكم لتشغيل الطاقة الكهرومائية يعتمد على تقليل قيم الضغط الرئيسية على جسم السد: دراسة حالة سد الموصل

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قسم الموارد المائية, كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

الغرض من هذه الدراسة هو فحص الاهتزازات الناتجة عن عمليات توليد الطاقة الكهرومائية من أجل تحسين سلامة السدود. هناك جزءان رئيسيان للدراسة. في الجزء الأول ، تم استخدام ANSYS–CFX لتوليد نموذج ثلاثي الأبعاد (3D) بحجم محدود (FV) لمحاكاة وحدة توربين فرانسيس الرأسية في محطة الطاقة الكهرومائية في سد الموصل. تم تحويل نتيجة نمط الضغط لنموذج التوربينات إلى جسم السد لإظهار كيف يؤثر تشغيل وحدة التوربين على استقرار السد. تم فحص ظروف خزان المنبع ومعدلات التدفق المختلفة وفتح بوابة المدخل بالكامل. في الجزء الثاني من هذه الدراسة ، تمت محاكاة نموذج ثلاثي الأبعاد لسد الموصل باستخدام برنامج ANSYS. يتم نقل نمط ضغط الماء الخاص بنموذج التوربينات التشغيلي إلى منطقة التوربينات المشتركة في السد. تم فحص اعلا و أوطأ منسوب لمياه الخزان في مقدمة السد. تم إنشاء برنامج تحكم اعتمادًا على نتائج نموذج الإجهاد الأساسي التي تم جمعها لتشغيل محطة الطاقة الكهرومائية بأقل ضغط رئيسي على جسم السد. يعزز هذا البحث نظام تشغيل التوربينات ، ويقلل من الضغط الواقع على جسم السد ويزيد من العمر التشغيلي للسد.

الكلمات الرئيسية: عنفة فرانسيس ، ANSYS ، الإجهاد الرئيسي ، سد الموصل.

1. INTRODUCTION

Many recent studies and research have been conducted to investigate the effect of vibrations from hydropower plant operations on dams. Some studies related to dams and hydropower plants, in addition to turbines, with knowledge of the effect of their operation. **(Jafari and Davoodi, 2004)** simulated a 3-D model of an embanked dam using ANSYS Software. **(Wel and Zhang, 2010)** developed a 3-D numerical model for a hydropower plant body by utilizing the ANSYS program to determine the stress and strain in the body of the powerhouse. The pressure distribution, acceleration, and frequency are present inside the powerhouse.

(Li et al., 2018) investigated the dynamic behavior of hydropower with six vertical Kaplan turbines and an earth-fill dam. In the first investigation stage, ANSYS-CFX created a 3-D finite element model to simulate a single vertical Kaplan turbine unit. In the second stage of the investigation, a 3-D FE earth-fill dam model was made using an ANSYS-static modeling methodology. The turbine-shared zone of the dam body is affected by the water pressure pattern formed around the boundary of the turbine model. The findings demonstrated that the distance from the turbine zone is inversely linked to variations in water pressure on the dam body. According to **(Ameen et al., 2018)**, embankment dams are made safer by minimizing the effects of vibrations generated by powerhouse operation inside the dam body. The study was divided into two parts. First part is concerned with ANSYS-CFX to construct a 3-D Finite Volume model of a vertical single Francis turbine unit. In the second part, ANSYS® is used to develop a 3-D finite element model of a rock-fill dam. The research enhances the turbine operating system, reducing stress on the dam body and increasing safety. **(Ameen et al., 2020)** considered the usage of a submerged weir at the downstream end of a draft-tube reaction turbine to stop upstream water level influences from altering the water flow's pressure and velocity. Building a submerged weir at the draft tube exit based on three different heights to develop a three-dimensional numerical model for the Kaplan and Francis turbines using the ANSYS CFX software tool. Negative pressure pulsation in Kaplan and Francis turbine draft tubes may be avoided. **(Laouari and Ghenaiet, 2016)** used Ansys-CFX to solve turbulent flow through a horizontal Francis turbine at a different operating stage. The study examined how cavitation influenced hydrodynamic performance and found cavitation pockets at the runner's trailing edge and a cavitation vortex rope in the draft tube. The output power and efficiency were raised to a critical level, where they subsequently began to stabilize. **(Gyanendra et al., 2020)** studied the cavitation in a prototype Francis turbine that has a capacity of 3 MW using the ANSYS CFX. Detailed flow field analyses are performed for 60 and 80 percent of parts loads, full loads, and overload operation at 120 percent with and without cavitation. **(Sibuea and Mirmanto, 2021)** observed how loading changes impact the occurrence of cavitation. Using Francis turbines with vertical shafts. The modeling and flow simulation software ANSYS CFX 18.2 was used. According to the findings, cavitation occurs when the load is at 40%, resulting in a vortex rope forming close to the draft tube and an area of very low pressure.

In this work, Mosul Dam and its powerhouse are represented by four vertical Frances turbines selected as a case study. The study includes two parts. In the first part, the primary emphasis is placed on simulating the functioning of turbines using a finite volume approach. In contrast, the second step involves employing a three-dimensional finite element analysis to check the stability of the dam body and the power plant.

2. METHODOLOGY

2.1 Mosul Powerhouse Description

Mosul Dam is the largest earth-fill dam in Iraq. The dam is located 60 km north of Mosul city. The powerhouse for the Mosul dam is designed as an integral part of the dam body. The powerhouse includes four Francis turbines with an installed total capacity of 750MW **(Adamo and Al-Ansari, 2016)**. The important information and location of the Mosul dam are outlined in **Table 1 and Figs. 1 and 2** are necessary for generating the turbine and dam 3-D FE models.

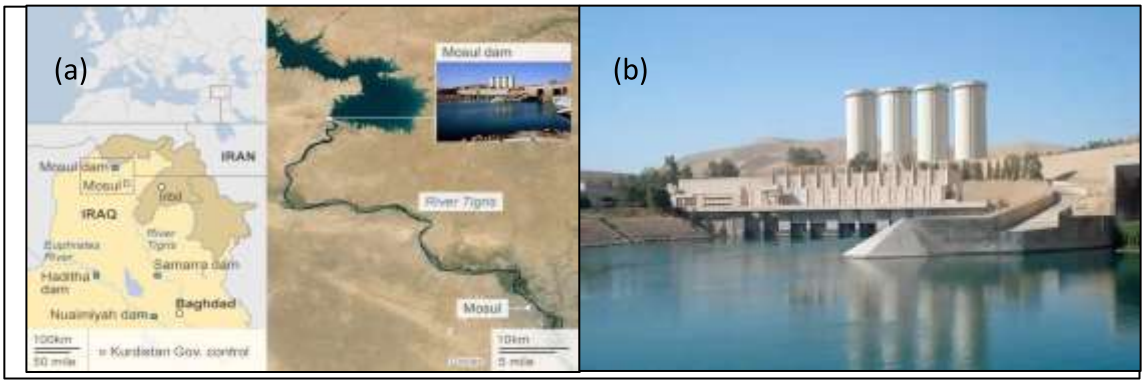


Figure 1. Mosul dam, a) location, b) Downstream view of the main dam showing downstream outlets **(Adamo and Al-Ansari, 2016)**.

Table 1. General data about the power plant.

Item	Unit	Qty
Location of Mosul dam		36°37′49″N, 42°49′23″E
Dam Dimensions		
Max. Dam height	m	113
Length of dam	m	3400
Crest length	m	2214
Crest width	m	10
Max. width of the base of the dam	m	650
Hydraulic Information		
Type of turbines		Vertical Francis
Install capacity	MW	750
Distance between the units	m	27
Head net rated	m	72.3,66.4,42.3
Discharges	(m^3/s)	280,260,210
Next ability	MW	193,155,77
Elev. Of spiral casing	m a.s.l	247.5
Inlet diameter of penstock	m	8
Runner diameter	m	6
Width outlet of draft tube	m	3
Length outlet of draft tube	m	10

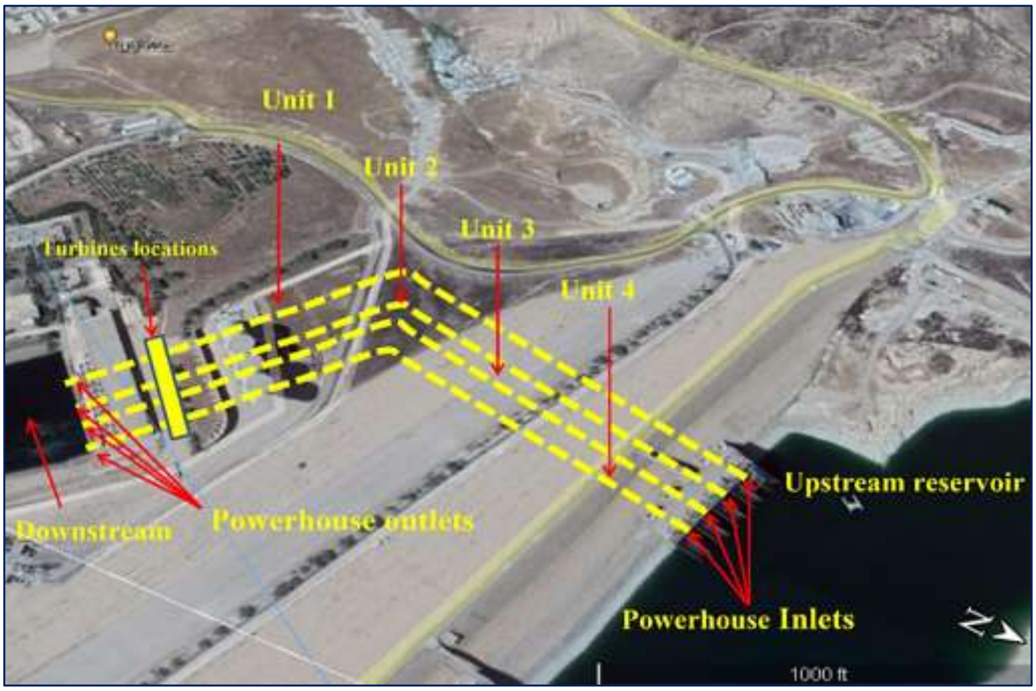


Figure 2. Top view of Mosul Dam with powerhouse details.

2.2 (3-D) Numerical Simulation of Mosul Turbine

A single vertical Francis turbine from the Mosul hydropower plant was selected as a case study to simulate the turbines' operational impact on the embanked dams. A three-dimensional numerical finite volume turbine model was generated by using ANSYS-CFX. The model included the inlet, penstock, runner, spiral casing, draft tubes, and outlets. **Figs. 3 and 4** show the dimensions and mesh details of the turbine model.

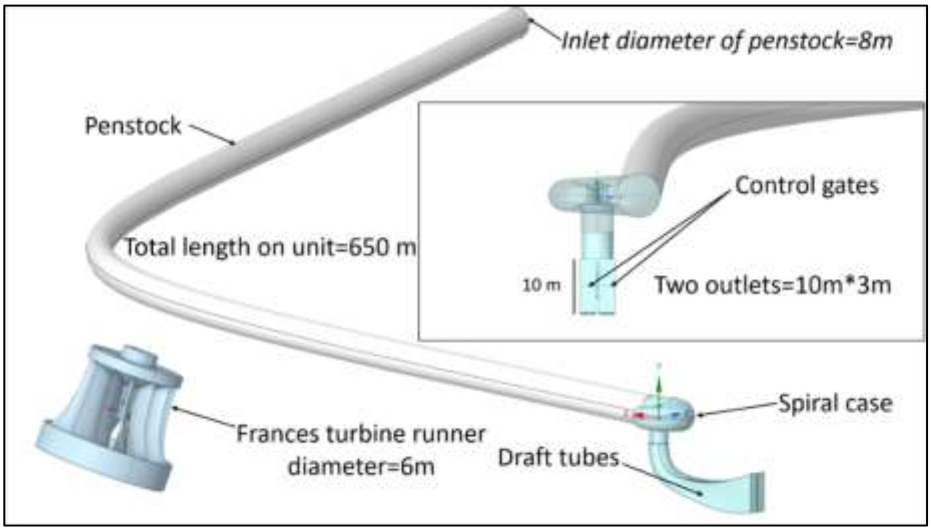


Figure 3. (3-D) Turbine Model of the Frances Turbine in Mosul dam Powerhouse.

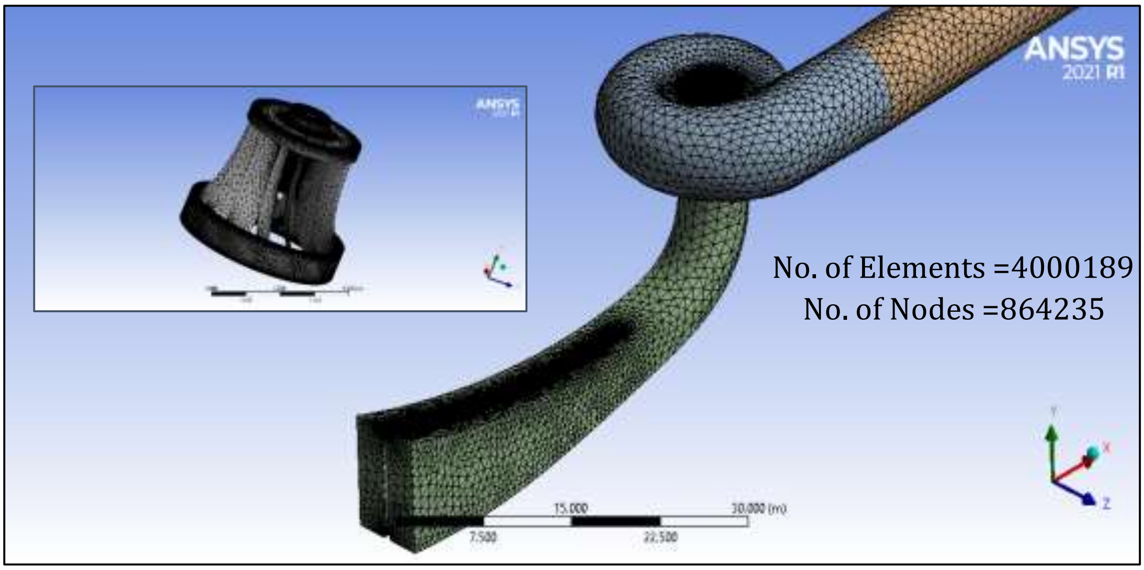


Figure 4. Vertical Francis unit (3-D) model with mesh details.

2.3 (3-D) Numerical Simulation of Mosul Dam

A 3-D FE numerical dam model was created to determine the effect of the vibration generated by operating the powerhouse on the embankment dam. The dam model, including the powerhouse portion, was generated using ANSYS software with a dimension of 650 m by 650 m in width and length. The dam-powerhouse models include a 113 m foundation depth. **Figs. 5 and 6** show the Mosul dam model, including the foundations and the powerhouse represented by four turbine units.

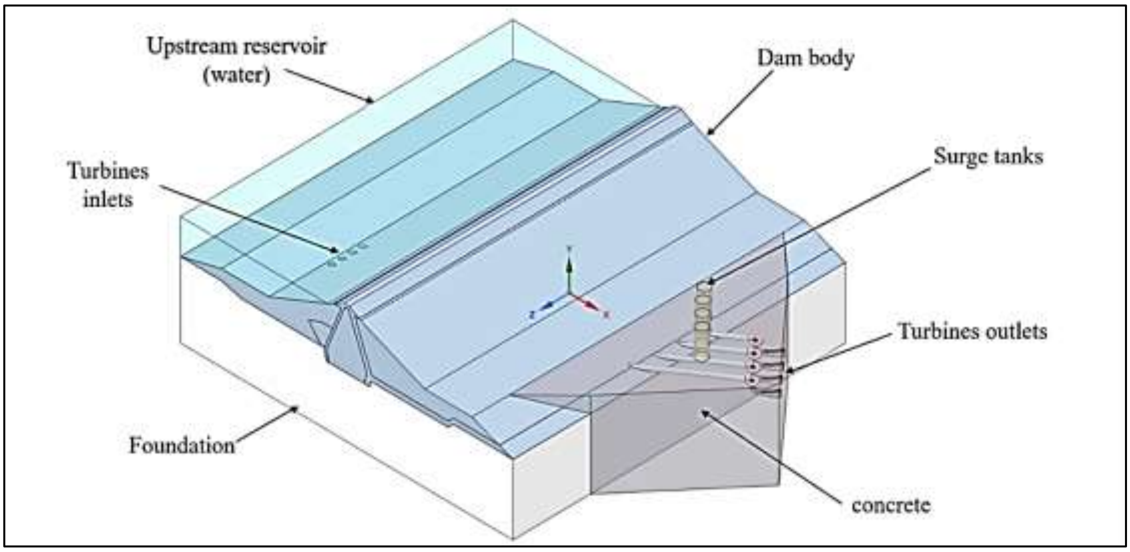


Figure 5. (3-D) model of the Mosul dam, including views of the turbines.

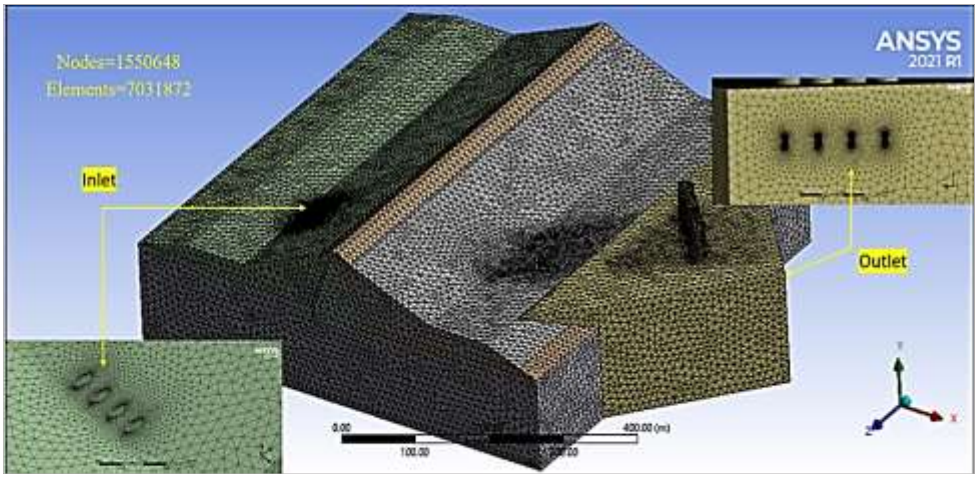


Figure 6. (3-D) Finite element model of the Mosul dam.

2.4 Hydraulic Simulation of Turbine Model

The k-Ɛ range turbulence model represents turbulent flow through the turbine unit, especially near the turbine runner, where streamlines display random motion **(Hidalgo et al., 2022)**. The three-dimensional numerical model based on the finite volume method is utilized to solve the Reynolds-averaged Navier-Stokes equations and differentiate between the unsteady incompressible flow within the turbine unit while operating under the different head and discharge ranges **(Yousif et al., 2015)**. For all simulations, the computational fluid dynamics (CFD) approach was employed **(Alwan and Azzubaidi, 2021)**. The required hydraulic data (collected from engineering reports such as the water levels upstream and downstream of the dam and discharge range) is crucial for generating and running the 3-D FE model. The Mosul Hydropower Plant's hydraulic data are shown in **Table 2**.

Table 2. Hydraulic data of the Mosul powerhouse turbine, including up-stream water levels (U/S.W. L), the flow rate (Q), the velocity (V), and the rotational speed of the turbine runner (N).

No	**U/S.W. L (m)**	**Net head (m)**	**N_s (rpm.kW/m)**	**Q (m^3/s)**	**P (kW)**	**V_{inlet} (m/s)**	**N (rad/s)**
Mosul turbine							
1	300	42.3	0.2828	210	72328	4.1778	2
2	322	66.4	0.2245	260	140568	5.1725	2
3	330	72.3	0.2149	280	164832	5.5704	2

The specific speed (N_s) is calculated such as:

$$N_s = \frac{1.924}{{H_n}^{0.512}} \tag{1}$$

While the water power (P) is calculated such that:

$$P = \eta.\rho.g.Q.H \tag{2}$$

2.5 Analysis of the Dam's Dynamic Behavior with Connections to Turbines

The 3-D FE, numerical dam model, was used to determine the principal stress variation with the change of upstream water level from the maximum drawdown level to the flood level. The soil's physical properties of the dam foundation were defined in the model depending on the engineering reports. **Table 3** shows the material physical properties of the dam-powerhouse model. ANSYS-CFX was used to do the modeling necessary to convert the pressure to the dam model. ANSYS-Static Structural tools were used to translate the pressure from the turbine units to the common zone between the dam and the powerhouse to calculate the principal stresses at specified places in the dam body. **Fig. 7** shows the selected points in the Dam bodies used for measuring the principal stress according to the number of the operating turbine.

Table 3. The physical properties of the materials used in the Mosul dam **(Yunis et al., 1999).**

	Modulus of Elasticity	**Bulk Modulus of Elasticity**	**Mass density**	**Poisson's Ratio**
unit	GPA	GPA	kg/m^3	-
concrete	25	-	2400	0.2
water	-	2.07	1000	0.49
Clay core	35.215	-	2000	0.3
Filter material	35.215	-	2400	0.3
Shell alluvium	35.215	-	2900	0.3
Shell Conglomerate	35.215	-	2700	0.3
Foundation	54.936	-	1785	0.3

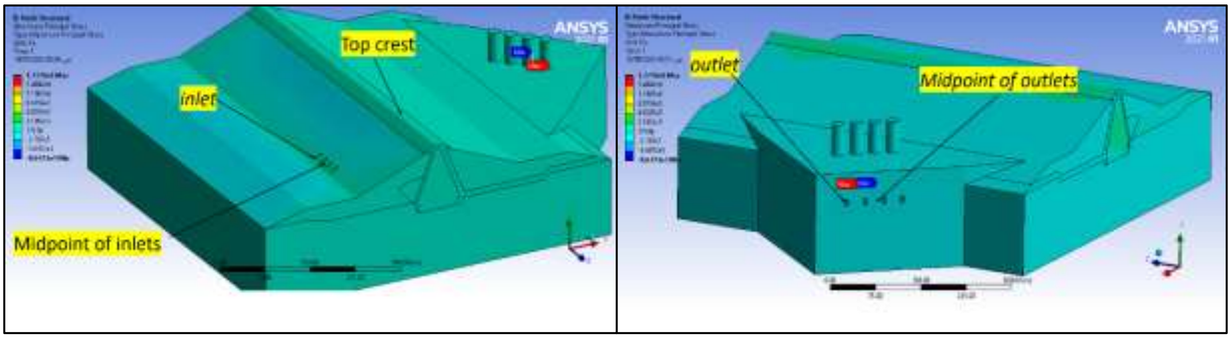


Figure 7. (3-D) FE model of Mosul dam with places of the principal stress measurement points.

3. RESULTS AND DISCUSSION

The results of running three-dimensional finite element numerical models for the Mosul embankment dam in conjunction with four turbine models are divided into two groups, which are summarized as follows:

1. The first group of results relating to hydraulic performance uses three-dimensional numerical finite-volume turbine models. These models were created by selecting a single Francis turbine unit of the Mosul Dam powerhouse. This unit runs at different upstream reservoir water levels. The running turbine model results include velocity flow lines, the distribution of pressure inside the turbines, and the total head at the turbine intake.
2. The second group of results was produced by combining 3-D finite volume turbine models with 3-D finite element dam models. The dam-turbines framework takes into account every possible operation of the turbines. The model runs with the minimum and maximum reservoir water levels when the upstream intake gates open completely. The principle stresses were determined in the selected locations of the three-dimensional dam model.

3.1 (3-D) Turbines Model

Table 4 presents the percentages of the energy differential between the total head at the turbine's intake and the upstream water levels using a numerical model, where (H_T) is the total head at the inlet of the Mosul turbine units depending on the inlet pressure model results, ($v^2/2g$) is the velocity head, (p/γ) is the pressure head, (Z) is the elevation head. The turbine model was run with varying water levels given in **Table 2**.

Table 4. Calculating the total head and the difference in energy at the Mosul turbine units' inlet.

Mosul Turbine									
No.	U/s.W.L. (m)	Q (m^3/s)	V Inlet (m/s)	P Inlet (KPa)	$v^2/2g$ (m)	p/γ (m)	Z (m)	H_T (m)	Energy difference %
1	300	210	4.1778	170	0.889	17.32	283	301.21	0.40
2	322	260	5.1725	388.45	1.363	39.29	283	323.96	0.60
3	330	280	5.5704	426.55	1.581	43.48	283	328.06	0.58

The results showed that the maximum difference between the total head at the inlet of the turbine and the water level upstream of the Mosul Dam is 0.6 percent. Comparing the total head at the inlets of the turbine model with the upstream water level is a great way to assess a model's accuracy. **Fig. 8** shows the consistency between the upstream reservoir water levels, which vary from the maximal and minimal upstream water levels with the total head at the turbine inlet.

The total head is evaluated as:

$$H_T = \frac{v^2}{2g} + \frac{p}{\gamma} + Z \tag{3}$$

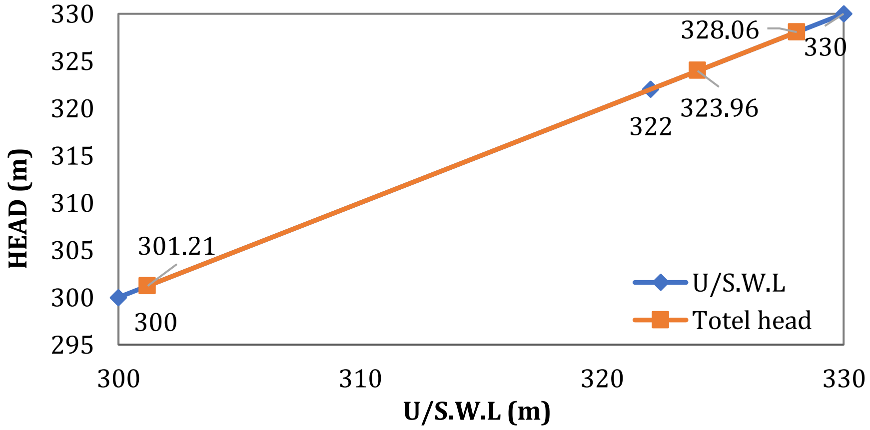


Figure 8. The total estimated head from operating the numerical model of the Mosul turbine unit.

The velocity distribution of Mosul turbine models is shown in **Fig. 9a**, with the maximum upstream water level being 330 above sea level. According to the continuity equation, the velocity at the turbine runner reaches the maximum values at the contacted cross-sectional area surrounding the turbine runner. The results showed that the maximum water velocity occurred at the location of the turbine runner, namely 25.07m/s, for a discharge of 280 m^3/s in the Mosul turbine. **Fig. 9b** shows the pressure distributions of the Mosul turbine unit. The pressure distributions are inversely related to the velocity distributions according to the energy equation. After the turbines have operated for a while, the lowest pressure values obtained in the turbine draft tube are more than the cavitation pressure **(Liu et al., 2005)**. The results regarding velocity and pressure from this investigation are consistent with those from the modeling carried out by **(Li et al., 2018; Ameen et al., 2018)**.

3.2 Optimal Power Plant Operation

Understanding the hydropower operation effects on the dam body must be managed to ensure that the dam operation is safe and sustainable. The hydropower in Mosul Dam, represented by four vertical Frances turbines, ran at different reservoir water levels. The boundary pressure pattern results from the running turbine model were transformed into the common connection area between the dam body and powerhouse. The dam-powerhouse numerical model runs using ANSYS software, and the boundary conditions that include the upstream reservoirs water level (represented by hydrostatic pressure and weight of Water), the dam weight and foundation, and the pressure pattern that transformed from the turbine model for the same Water levels. The physical properties of dam body materials, foundation materials, and Water were defined. The model runs in different reservoir conditions to get optimal turbine operation that gets minimum principle stresses in critical parts of the dam-powerhouse system. This is of the utmost importance for the aim of acquiring procedures in the setup of the hydropower system that is trustworthy and practical. The dam-powerhouse model with dimensions 650 m width and 650 m height and the four vertical Frances turbine units are shown in **Fig. 10**. According to the findings; the pressure dropped significantly as the flow passed around the turbine runner before decreasing progressively in a random manner under the turbulent flow characteristics from the intake to the exit.

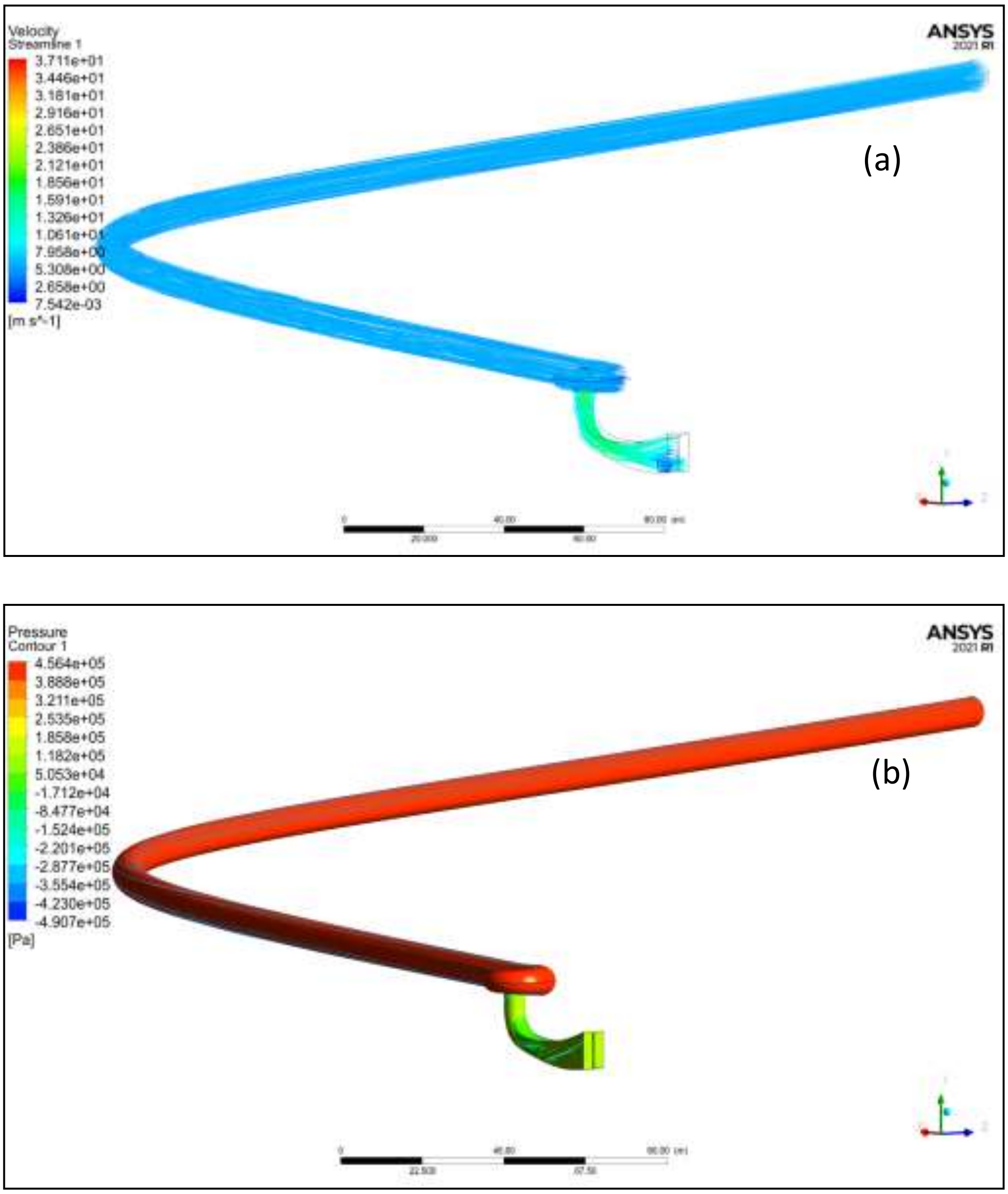


Figure 9. (a) Velocity flow lines in Mosul turbine unit (b) The pressure distribution in Mosul turbine unit.

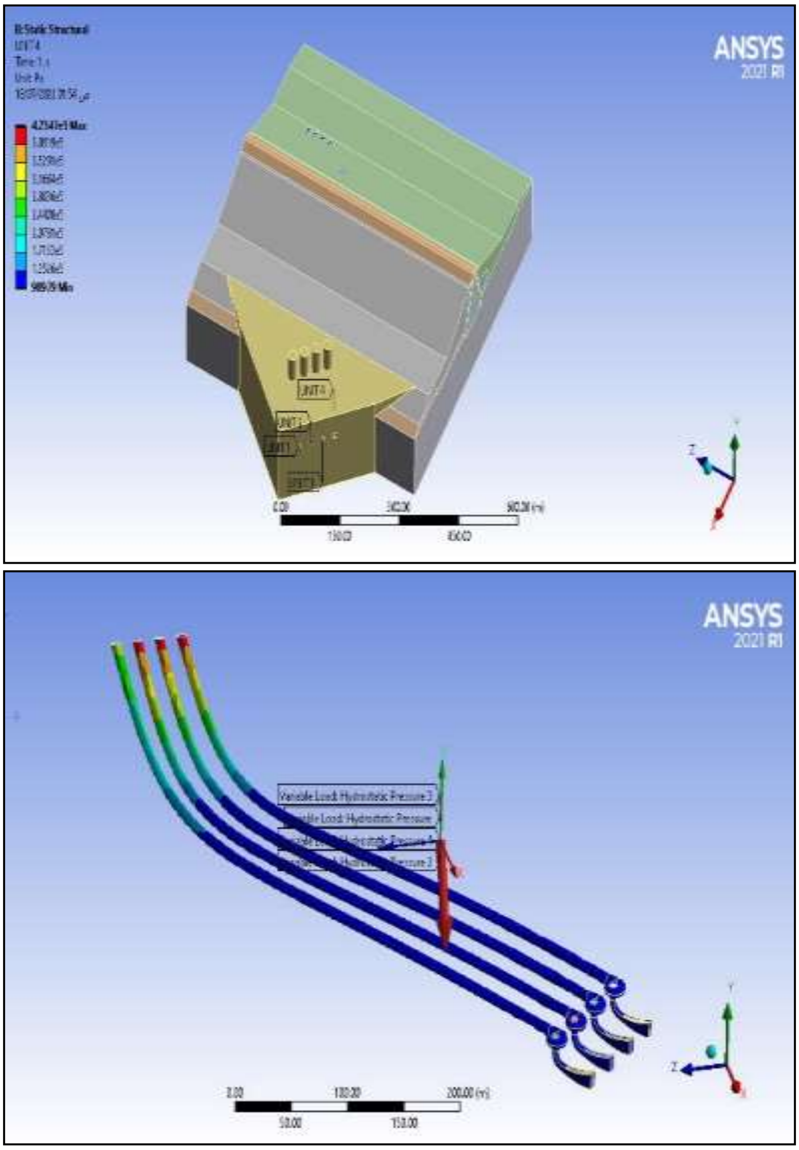


Figure 10. A (3-D) numerical model that includes the process of pressure transformation from the turbine unit to the Mosul dam.

And the results show that the estimated principal stresses at the selected point of the dam body were consistent with the dam's lowest and highest water levels upstream and the impact of running turbines. The effect of running turbines on the dam body is represented by transforming the boundary pressure pattern that represents the results of running the ANSYS-CFX-turbine model to the dam-powerhouse framework. To account for all scenario outcomes regarding the operation of the turbines, the dam-powerhouse framework ran 32 times with the highest and lowest upstream water levels, 16 times with the highest, and 16 times with the lowest upstream water levels. The numerical findings demonstrated that the greatest and lowest principal stresses that are located close to the turbine border, their values change depending on the distance of the selected point from the effect of the turbines, as well as changes in the upstream water level depending on values for the highest and lowest water levels. **Figs. 11 and 12** show the principal stress values at the selected point of Mosul Dam with maximum and minimum upstream water levels, respectively. **Tables 5**

and 6 provide a statistical overview of the critical values of the stresses associated with the highest and lowest water levels for the Mosul hydropower plant after assessing the data for the inspected dam. According to the results of the principal stresses and as a final statistical analysis, the categorization of the stresses in the models for the Mosul Dam is shown in **Table 7**, from minimum to maximum. According to this categorization, the second objective of this study has been accomplished.

Fig. 13 illustrates how the optimal powerhouse should be operated for the best possible results. The various kinds of soil used to fill embankment dams can withstand varying degrees of stress. The primary objective of the current study is to determine how much the stresses will increase due to the vibrational effects caused by the operation of the powerhouse.

Table 5. Statistical analysis of the Principal Stress results of the Mosul dam according to the running turbines at Maximum upstream Water level.

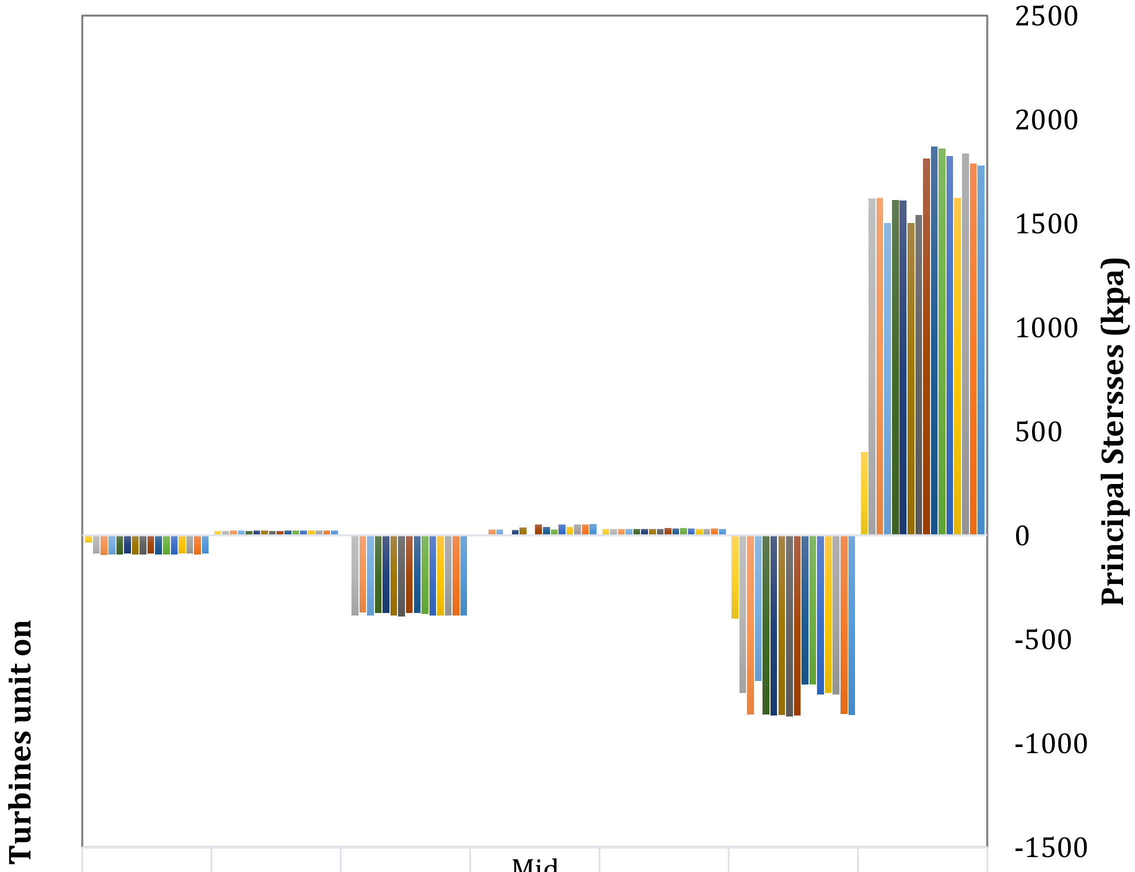
	Inlet	**Mid Inlet**	**Outlet**	**Mid Outlet**	**Top crest**	**Min.**	**Max.**
Maximum (kPa)	-89.411	22.853	-370.2	52.942	33.764	-700.2	1870.3
Minimum (kPa)	-95.301	20.469	-389.0	0.999	28.022	-869.6	1500.5
Difference (kPa)	7.431	2.384	18.8	51.943	5.742	169.4	369.8
Percent (%)	8.57	10.43	5.07	98.11	17	24.19	19.77

Table 6. Statistical analysis of the Principal Stress results of the Mosul dam according to the running turbines at Minimum upstream Water level.

	Inlet	**Mid Inlet**	**Outlet**	**Mid Outlet**	**Top crest**	**Min.**	**Max.**
Maximum (kPa)	-86.690	16.881	-255.8	40.123	19.591	-603.7	1693.8
Minimum (kPa)	-94.121	13.376	-263.9	0.662	18.494	-788.5	1403
Difference (kPa)	5.89	3.505	8.1	39.461	1.097	184.8	290.8
Percent (%)	6.58	20.76	3.16	98.35	5.59	30.6	17.16

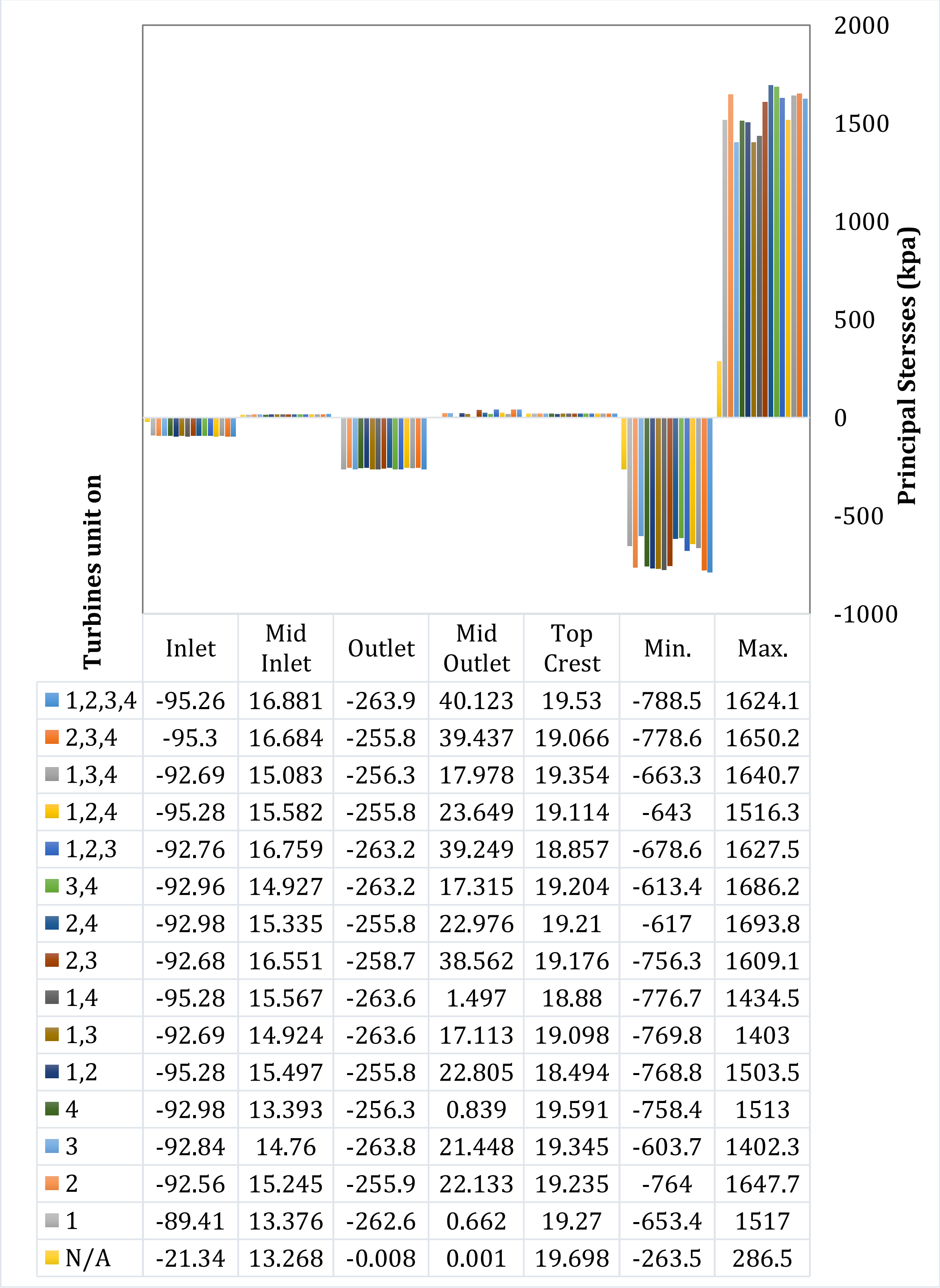
Table 7. Mosul's dam's principal stress categorization.

Principal stress range (kPa)	**Ranking**	**Indicator**
$1400 \leq \sigma_{max} < 1500$	Excellent	🟦
$1500 \leq \sigma_{max} < 1600$	good	🟩
$1600 \leq \sigma_{max} < 1700$	Acceptable	🟨
$1700 \leq \sigma_{max}$	Not acceptable	🟥



	Inlet	Mid Inlet	Outlet	Mid Outlet	Top Crest	Min.	Max.
🟦 1,2,3,4	-87.204	22.853	-384.7	52.942	29.783	-863.1	1777.6
🟧 2,3,4	-92.24	22.749	-383.8	51.929	30.612	-858	1787.7
⬜ 1,3,4	-86.69	21.536	-383.8	50.029	29.437	-765	1835.3
🟨 1,2,4	-87.209	21.945	-384.2	39.518	30.135	-756.9	1621.6
🟦 1,2,3	-91.167	22.796	-384.3	51.57	31.758	-764.8	1823.5
🟩 3,4	-91.183	21.448	-377.1	27.209	33.289	-716.5	1858.5
🟦 2,4	-92.256	21.835	-373.7	38.583	31.663	-716.4	1870.3
🟫 2,3	-87.228	20.572	-373.6	50.558	33.764	-866.5	1811
⬛ 1,4	-92.257	20.572	-389	2.01	29.659	-869.6	1539.5
🟫 1,3	-91.184	21.467	-384.3	36.951	29.336	-864.1	1501.8
🟦 1,2	-87.211	21.912	-372.9	25.18	29.437	-865.3	1609.6
🟩 4	-92.259	20.469	-373.7	1.373	30.25	-859.7	1611.3
🟦 3	-91.187	21.376	-383.8	25.993	29.934	-700.2	1500.5
🟧 2	-94.121	21.789	-370.2	26.286	28.022	-861.3	1621.9
⬜ 1	-87.23	20.518	-384.3	0.999	30.059	-756.7	1618.1
🟨 N/A	-32.827	20.412	-0.222	0.002	28.864	-400.05	400.4

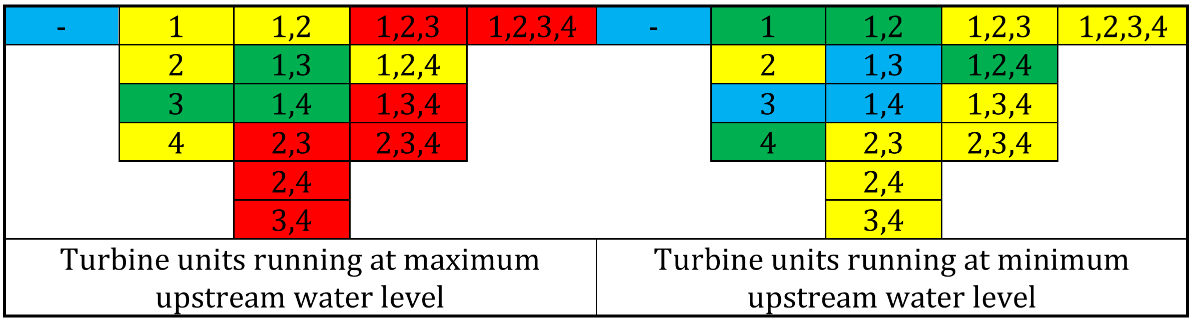
Figure 11. The Principle Stress values in the selected points of Mosul dam body according to running turbine units in Maximum Water (kPa).



Turbines unit on	Inlet	Mid Inlet	Outlet	Mid Outlet	Top Crest	Min.	Max.
🟦 1,2,3,4	-95.26	16.881	-263.9	40.123	19.53	-788.5	1624.1
🟧 2,3,4	-95.3	16.684	-255.8	39.437	19.066	-778.6	1650.2
⬜ 1,3,4	-92.69	15.083	-256.3	17.978	19.354	-663.3	1640.7
🟨 1,2,4	-95.28	15.582	-255.8	23.649	19.114	-643	1516.3
🟦 1,2,3	-92.76	16.759	-263.2	39.249	18.857	-678.6	1627.5
🟩 3,4	-92.96	14.927	-263.2	17.315	19.204	-613.4	1686.2
🟦 2,4	-92.98	15.335	-255.8	22.976	19.21	-617	1693.8
🟫 2,3	-92.68	16.551	-258.7	38.562	19.176	-756.3	1609.1
⬛ 1,4	-95.28	15.567	-263.6	1.497	18.88	-776.7	1434.5
🟫 1,3	-92.69	14.924	-263.6	17.113	19.098	-769.8	1403
🟦 1,2	-95.28	15.497	-255.8	22.805	18.494	-768.8	1503.5
🟩 4	-92.98	13.393	-256.3	0.839	19.591	-758.4	1513
🟦 3	-92.84	14.76	-263.8	21.448	19.345	-603.7	1402.3
🟧 2	-92.56	15.245	-255.9	22.133	19.235	-764	1647.7
⬜ 1	-89.41	13.376	-262.6	0.662	19.27	-653.4	1517
🟨 N/A	-21.34	13.268	-0.008	0.001	19.698	-263.5	286.5

Figure 12. The Principle Stress values in the selected points of Mosul dam body according to running turbine units in Minimum Water (kPa).

A classification program was developed to operate the turbine units in the Mosul hydropower plant based on the principal stress results at the critical points of the dam body. According to the categorization listed in **Table 7**, the control program utilized for running turbines depends on minimizing the maximum stress values. **Fig. 13** shows a control program that may be used to operate Mosul turbines. This program depends on reducing principal stress values in the selected points and is organized according to the categorization presented in **Table 7**.



-	1	1,2	1,2,3	1,2,3,4	-	1	1,2	1,2,3	1,2,3,4
	2	1,3	1,2,4			2	1,3	1,2,4	
	3	1,4	1,3,4			3	1,4	1,3,4	
	4	2,3	2,3,4			4	2,3	2,3,4	
		2,4					2,4		
		3,4					3,4		
Turbine units running at maximum upstream water level					Turbine units running at minimum upstream water level				

Figure 13. Control program for the turbines of the Mosul power plant based on minimizing principal stress.

4. CONCLUSIONS

A dam safety study should include the functioning of the dam's power plant. The primary objective of the current research was to integrate the vibrational impact caused by the operation of reaction turbines. A three-dimensional (3-D) turbine model is connected with the dam model to simulate the pressure pattern in the common area between the dam and the powerhouse. The results show that the estimated principal stresses at the selected point of the dam body were consistent with the dam's lowest and highest water levels upstream and the impact of running turbines. The effect of running turbines on the dam body is represented by transforming the boundary pressure pattern that represents the results of running the ANSYS-CFX-turbine model to the dam-powerhouse framework. To account for all scenario outcomes regarding the operation of the turbines, the dam-powerhouse framework ran 32 times with the highest and lowest upstream water levels, 16 times with the highest, and 16 times with the lowest upstream water levels. The results show that the maximum principal stress difference equals 369.8 kPa when the turbines run at the maximum upstream water level. The maximum principal stress difference equals 290.8 kPa when the turbines run at the maximum upstream drawdown water level. The outcomes of this research will help our knowledge of the operational strategies used in the energy market, which tend to increase the equipment lifespan of hydropower facilities by increasing load variations.

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