Numerical investigation of the flow characteristics in the vicinity of pressure conduit's gates

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Abstract

Bottom outlet is one of the related hydraulic structures of dams used to control initial water volume in reservoir and to help the spillways discharge capacity in floodwaters. Designed elements of bottom outlet such as control gates must be able to properly act to regulate downstream flow in entirely closed and semi-open situation. Bottom outlets which work with high heads, may create intense change in velocity and pressure field near the control systems (gates) by high velocity that probably causes cavitation phenomenon and unusual vibration on the structure's wall and conduit to happen. In the present research, characteristics of the flow, such as momentary and average flow's pressure and velocity near the service gate, cavitation index and gate vibration frequency in reservoir normal head (100 m) at various service gate openings were extracted and analyzed using numerical model of Seymareh dam's bottom outlet with FLOW 3D software and RNG(K-ε) turbulence model. The results of this research will help to appropriately understand the hydraulic phenomena occurred around outlet gates.

Keywords: Control Gate, Flow Characteristics, FLOW 3D, Seymareh Dam.

1. INTRODUCTION

Dams are used to provide water for industry, drinking and agriculture needs, also to regulate the river excessive flow and flood control. Generally, dams are divided into two categories, earth fill dams and concrete dams which have different related hydraulic structures. Bottom outlet is one of them, which is used to control initial water volume in the reservoir and to help the spillway discharge capacity in floodwaters [1]. After studying the cause for failure of bottom outlets in damaged dams, it has been obvious that cavitation phenomenon and gate vibration are known as the main problems [2].

According to intense flow's sensitivity on geometric parameters of the outlet conduit, any changes in these parameters will cause fluctuation in velocity and pressure fields. Due to high-velocity flow and existence of irregularities in the conduit surface, separation of the flow from the conduit bed may occur, and the pressure will reduce locally. If the flow's pressure becomes less than the water vapor pressure, the state of the water will change from liquid to gas and vapor cavity bubbles will be formed. The vapor cavities may move into a zone of higher pressure with the flow, so they collapse and send out high pressure shock waves; if the cavities collapse near the conduit surface, there the materials will be damaged at the boundary and this will cause an unusual vibration in the control structures such as control gates in bottom outlet. The downstream of the service gate, the area between the emergency and the service gate (in the case of operating the gates together), and also in gate slots, where an unusual surface stands against the flow, are the most potential areas of damage [3].

So in this research characteristics of the flow, such as momentary and average flow's pressure and velocity near the service gate, cavitation index and gate vibration frequency in reservoir normal head (100 m) at various service gate openings were analyzed using numerical model of Seymareh dam's bottom outlet with FLOW 3D software and RNG (K-ε) turbulence model to assess the probability of damage.

Roun shi et al. (2005) experimentally studied the aerators' hydraulic performance used on the floor of Goupitan dam's bottom outlet. Their results showed that the rate of entranced air increases with a decrease in aerator's downstream bed slope which has an effective role to protect the bottom outlet conduit against cavitation damage [4].

Daneshman et al. (2007) experimentally analyzed the hydraulic flow characteristics through a Sivand dam's bottom outlet conduit at various service gate openings. The results of their research indicated that, for service gate openings which are more than 85%, the amount of turbulence in emergency gate slots increases. To overcome this problem, it is recommended to reduce the emergency gate slot's width and the cavitation index should be more than the critical amount (0.2) at all openings [5].

Daneshman et al. (2014) experimentally and numerically studied the hydraulic flow parameters and forces effecting the gate in the various service gate openings using Finite Element method in Shahryar dam's bottom outlet. Their results showed that the cavitation index was proper and the service gate vibration frequencies were not close to critical value at all openings. They also found that the minimum amount of discharge coefficient occurs at 20% gate openings [6].

2. BASIC EQUATIONS OF FLOW FIELD

The basic equations of fluid motion are the continuity and momentum equations which are expressed as equation (3), (4) for incompressible and turbulent flow with constant viscosity and density [7].

$$\frac{\partial U_i}{\partial x_i}=0 \tag{3}$$

$$\frac{\partial U_i}{\partial t}+U_j\frac{\partial U_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(v\frac{\partial U_i}{\partial x_j}-\overline{u_i'u_j'}\right) \tag{4}$$

Where x_i shows Cartesian system, t is time, ρ is fluid density and $\overline{P}$ ، U_i ، $u_i'u_j'$ are average pressure, velocity and Reynolds stress tensor, respectively.
Free water surface is defined by means of volume of fluid (VOF) and computing the function, F (x, y, z, t). This function represents the volume of fluid #1 per unit volume and satisfies the equation.

$$\frac{\partial F}{\partial t}+\frac{1}{V_F}\left[\frac{\partial}{\partial x}\left(FA_xu\right)+R\frac{\partial}{\partial y}\left(FA_yv\right)\right]+\frac{1}{V_F}\left[\frac{\partial}{\partial z}\left(FA_zw\right)+\xi\frac{FA_xu}{x}\right]=F_{DIF}+F_{SOR} \tag{5}$$

$$FDIF=\frac{1}{V_F}\left[\frac{\partial}{\partial x}\left(\upsilon_F A_X\frac{\partial F}{\partial x}+R\frac{\partial}{\partial x}\left(\upsilon_F A_y R\frac{\partial F}{\partial y}\right)\right)\right]+\frac{1}{V_F}\left[\frac{\partial}{\partial z}\left(\upsilon_F A_z\frac{\partial F}{\partial z}\right)+\xi\left(\frac{\upsilon_F A_X F}{X}\right)\right] \tag{6}$$

Where V_F is the fractional volume of flow, (u, v, w), A_X, A_y, A_z are velocity and fractional area of flow components in the coordinate directions (x, y, z), Respectively. When Cartesian coordinates are to be used, R is set to 1 and ξ is set to 0. The term F_{SOR} corresponds to the density source R_{SOR} in Eq (5); F_{SOR} is the time rate of change of the volume fraction of fluid #1 associated with the mass source for fluid #1.

The interpretation of F depends on the type of problem being solved. Incompressible problems must involve either a single fluid with a free surface or two fluids and no free surfaces. For a single fluid, F represents the volume fraction occupied by the fluid. Thus, fluid exists where F=1, and void regions correspond to locations where F=0. "Voids" are regions without fluid mass those have a uniform pressure assigned to them. Physically, they represent regions filled with vapor or gas whose density is insignificant with respect to the fluid density [8].

3. GENERAL CHARACTERISTICS OF SEYMAREH DAM AND RELATED FACILITIES

Seymareh dam, as a concrete double - arch dam (fig (1)), has two bottom outlets, their entrances are 620 and 640 m above the sea level respectively, therefore, they are 20 and 40 m above the river bed. Due to the plan and longitudinal profile number (1), the entrance bottom outlet shown in fig (2) and (3), is bell shape and it is 17.85 * 9.56 m (height * width). To prevent entering large objects, a concrete rack is used at the entrance of the conduit. The emergence and service gate are slider and radial, respectively. In this research characteristics of flow have been investigated in No. 1 bottom outlet which has 45.4 m length. Note that on 100% service gate opening the length of pipe flow is 36.5 m and free flow is 8.9 m. This bottom outlet has been designed for maximum discharge 654 ($^{m^3}/_s$) at 111/5 m upstream water head [9].

Figure 1. Location of Seymareh dam and its related structures (Seymareh Dam and Power Plant Website)

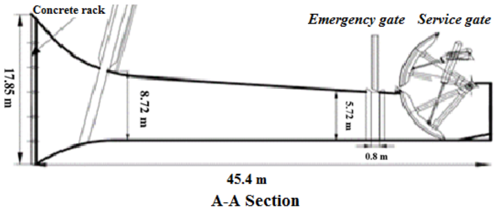

Figure 2. Longitudinal section of No. (1) Seymareh Dam's bottom outlet

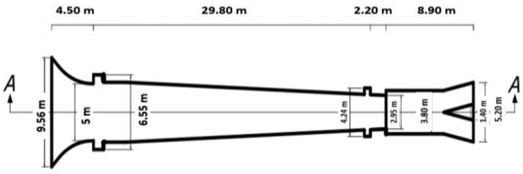

Figure 3. Plan of No. (1) Seymareh Dam's bottom outlet

4. NUMERICAL MODEL

The three-dimensional model is prepared in actual size using the plan and longitudinal bottom outlet's maps via AutoCAD 3D software, then it has been exported to FLOW 3D software with Stl format. According to the essence of basic equations, flow analysis starts with fixed boundary condition, and as time passes, the process reaches the steady state. The fluid is considered as a compressible and single phase fluid, the time of analysis assumed to be 30s. K-ε (RNG) is chosen as the turbulent model due to the advantage of Renormalization Group Instead of constant factors. To calculate the free surface profile, VOF model is used [10].

One of the effective issues for the accuracy of calculation in numerical models is the appropriate definition of boundary condition. In figure (4) and table (1), boundary condition of the model is shown. The wall and outflow boundary condition are set to wall and outlet flow and inlet boundary condition whose head equals to reservoir's head is set to specified pressure.

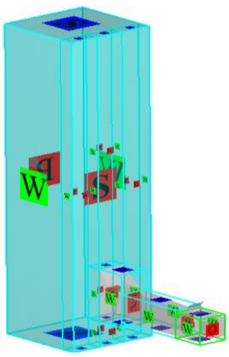

Figure 4. the blocks have been used in numerical mode

Table 1. The boundary condition of numerical model

Specified pressure	Model input
Outflow	Model output
wall	walls
Symmetry	The border of the between blocks
1.503.019	The total number of computational mesh

To identify the appropriate upstream reservoir dimension (length, width), the model is performed with different dimensions which are shown in the table (2). Due to the calculated flow velocity profiles at the different sections of bottom outlet conduit, it is observed that the flow velocity profiles have adopted on each other after the No.3. Reservoir dimension and increasing of dimension had not affected the velocity. So the size of 30 * 29.53 m is selected as upstream reservoir dimension.

Table 2. The boundary condition of numerical model

number of computational mesh	The reservoir dimensions, respectively: (width, length)	number of reservoir
50,592	9.53×10	1
219,443	19.53×20	2
507,500	29.53×30	3
884,268	39.53×40	4
1,126,650	44.53×45	5

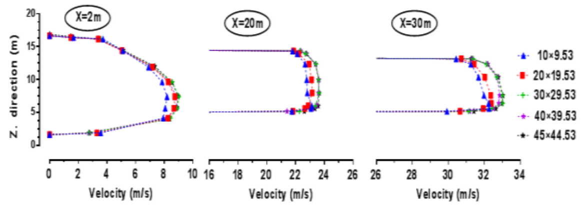

Figure5. The velocity profiles for different reservoir dimension at the section of 2 , 20 , 30 m from the conduit entrance

5. NUMERICAL MODEL VERIFICATION

In this research to verify the results of the numerical model, the average pressure value on the bed of the conduit and outlet discharge parameters in the normal head (100 m) of bottom outlet's hydraulic model are used. Verification is done at 30, 70, 100 and 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 service gate openings.

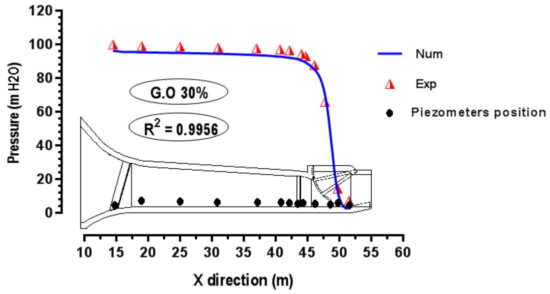

Figure 6. Average pressure variation along the conduit on the floor at 30% gate opening

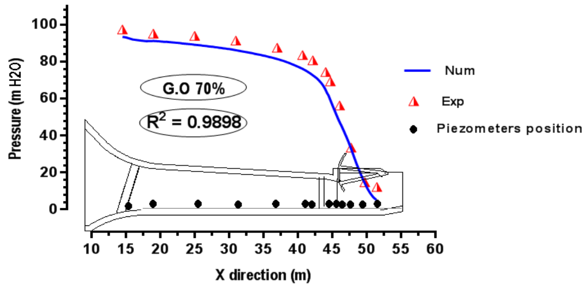

Figure 7. Average pressure variation along the conduit on the floor at 70% gate opening

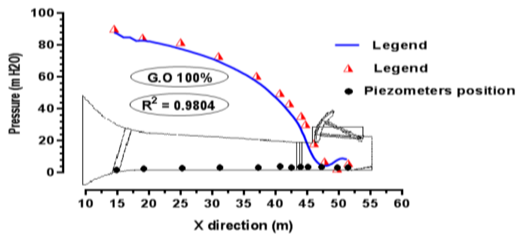

Figure 8. Average pressure variation along the conduit on the floor at 100% gate opening

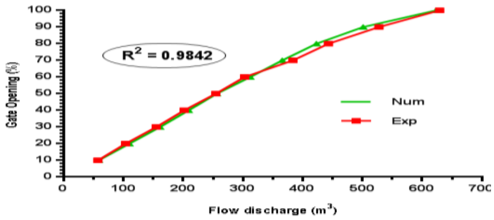

Figure 9. Outlet discharge variation at the different service gate opening

The results of figures 6 to 8 show that the most difference of average pressure value in the conduit bed happens at the downstream of service gate caused by intense turbulent flows at these areas, and resulted in an error by reading the pressure in the laboratory or exact calculation of the numerical model.

The obtained values for the correlation coefficient (R^2) in figures 6 to 9 show good agreement between the experiment and numerical results and confirm the numerical model results.

6. ANALYZE OF RESEARCH RESULTS

Velocity and pressure of the flow are two important parameters which have a basic role to identify the flow pattern at the downstream gate and anticipating the problems in bottom outlet conduit. Because of high velocity and pressure drop at the vicinity of control systems (gates) in the bottom outlets which work with high heads, the occurrence of cavitation damage is expected [11]. The improper design of bottom outlets geometry may cause negative pressure on the conduit walls and gate vicinity, therefore, gate structures encounter unusual vibrations. So studying these phenomena has an important role in designing safe hydraulic structures [12].

6. 1. THE FLOW PATTERN ALONG THE CONDUIT

By investigating the average flow's velocity and pressure on the floor of conduit for 4 service gate openings and moving toward the downstream conduit, due to reduction of cross section to the service gate, the flow velocity increases and the pressure reduces in figures 10 and 11. For less gate openings, velocity of the flow at the upstream of service gate is gradually increased, but in gate location it has a sudden increase. For the large gate openings, the slope of flow's velocity profile is steeply increased at the upstream conduit and at the gate location while the variation of flow velocity is small.

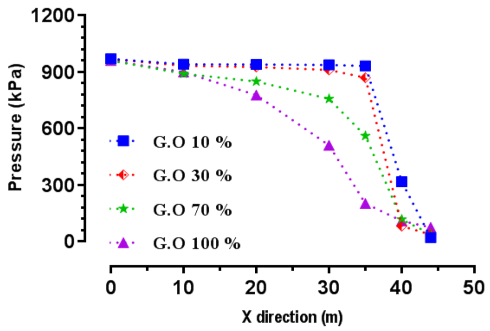

Figure 10. The longitudinal pressure profile on the floor of outlet for different gate opening (G.O).

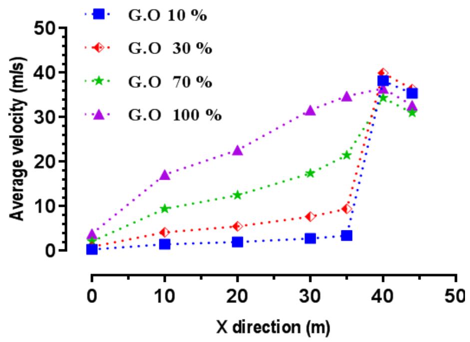

Figure 11. The longitudinal average flow velocity for different gate opening (G.O).

To identify possible damages, it is necessary to assess the flow pattern in this area for different gate openings due to the intense variation in velocity and pressure of the flow in vicinity of service gate (fig (10), (11)), which is caused by reduction of the cross section along the conduit. The figures of No. 12 to 15 show the flow velocity and pressure field around the service gate.

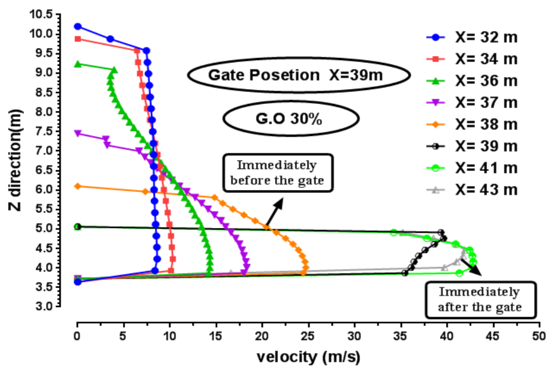

Figure 12. The profile of flow velocity distribution in vertical sections of outlet conduit in vicinity of service gate for 30% gate opening

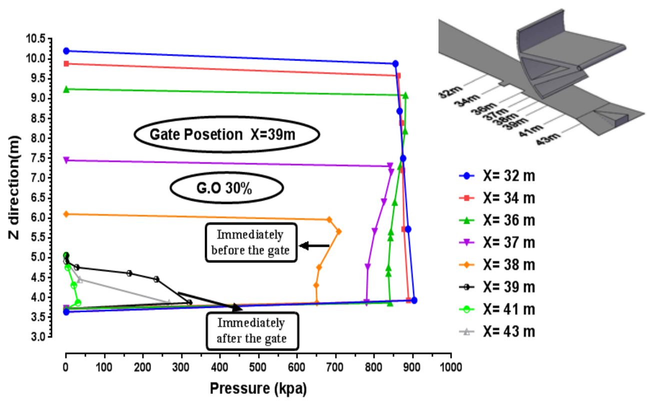

Figure 13. The profile of flow pressure distribution in vertical sections of outlet conduit in vicinity of service gate for 30% gate opening

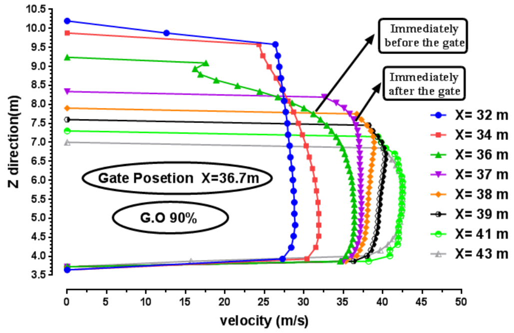

Figure 14. The profile of flow velocity distribution in vertical sections of outlet conduit in vicinity of service gate for 90% gate opening

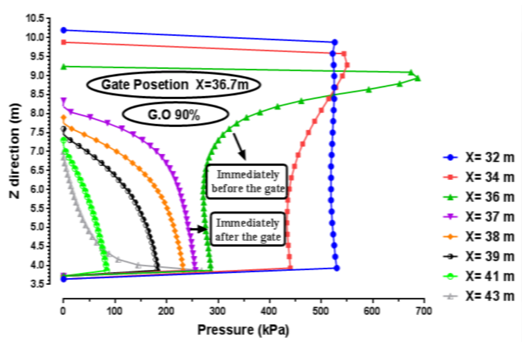

Figure 15. The profile of flow pressure distribution in vertical sections of outlet conduit in vicinity of service gate for 30% gate opening

As a result of the flow's velocity and pressure values in the vicinity of the service gate for 30% and 90% gate openings (figures 12 to 15), the large service gate openings influence the profiles of velocity and pressure further than the upstream of the gate; so that the changes of flow velocity and pressure profiles for the 30% and 90% service gate openings occur at 36m and 34m sections, respectively. By approaching the flow to the service gate, unlike the pressure in front of gate opening, the flow velocity increases in bottom levels, and by passing through the gate, it distributes fairly in a uniform manner.

6. 2. INVESTIGATION OF CAVITATION INDEX IN VICINITY OF SERVICE GATE

6. 2. 1. CAVITATION INDEX ON THE CONDUIT FLOOR

The cavitation index relationship representing the relation of hydraulic pressure energy to dynamic pressure would be reduced by the reduction of pressure and increasing of flow velocity. Consequently, the flow velocity and pressure investigation in figures of 10 to 15 show the increased intensity of velocity and decreased pressure more occur for the small gate openings. So the occurrence of cavitation phenomenon will be possible in this condition.

In figure18, by investigation the cavitation index variations at the bed of the conduit for various service gate openings, it is observed that the cavitation index is less than the critical value (0.2) for the 10, 20, 30, 40 and 80% of service gate openings from the 41m section to the end and for the 50 and 70% of gate openings from the 41m to 43m section, therefore, the occurrence of cavitation damage is possible. However, there is no probability of damage due to high cavitation index for 60, 90 and 100% of gate openings.

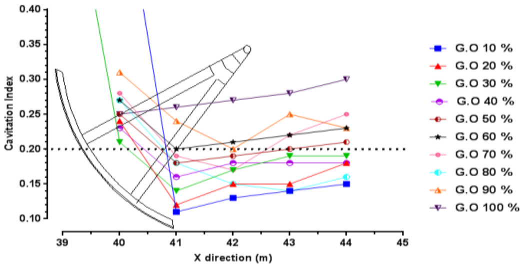

Figure 16. Cavitation index variation on the floor of conduit for the different service gate opening from the 40m to 45m of conduit entrance

6. 2. 1. CAVITATION INDEX ON THE CONDUIT WALLS AND CEILING

Figures NO. 17 and 18 show the cavitation index value at various sections of the wall for different service gate openings. The obtained results indicate that the cavitation index value is less than the critical value (0.2) for all the gate openings. For small gate openings, cavitation starts from the bottom of the gate and the damage will continue to the end of the conduit; and for most gate openings, cavitation occurs at the end of the conduit.

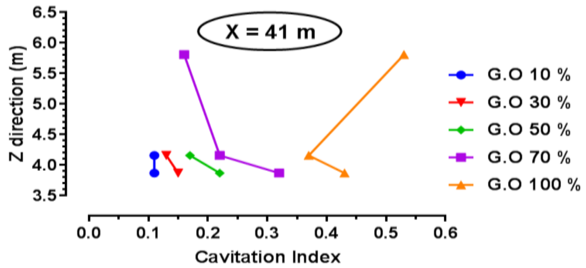

Figure 17. Cavitation index variation on the conduit wall for the different service gate opening at section of 41m from the conduit entrance

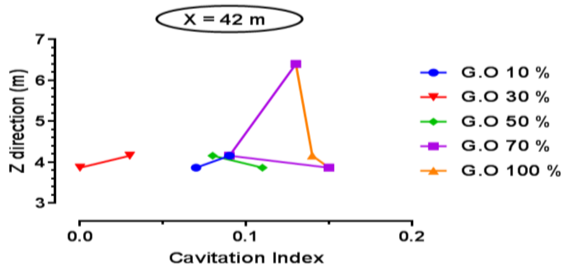

Figure 18. Cavitation index variation on the conduit wall for different service gate opening at the section of 42m from the conduit entrance

The value of this parameter for the conduit's ceiling is more than the critical value and the minimum obtained value equals to 0.46 which occurs in the section of 36m from the conduit entrance.

6. 2. FREQUENCY IDENTIFICATION OF HYDRODYNAMIC PRESSURE

Hydrodynamic pressure fluctuations could cause significant effects on gate structure, so the magnitude and frequency contents of the pressure fluctuations should be accurately investigated. In this section, hydrodynamic pressure time history for two gate openings analyzed. 20% and 40% gate openings have been selected to frequency identification analysis. In figure 19, power spectrum of hydrodynamic pressure in the condition of 20% opening for 5 different points is presented. As shown, all these points have similar spectrum and similar frequencies.

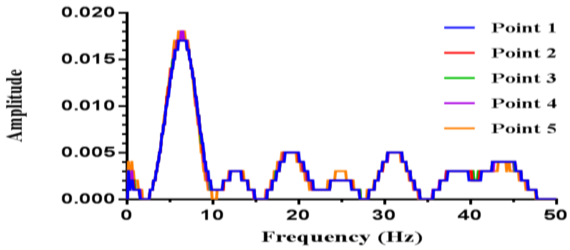

Figure 19. hydrodynamic pressure power spectrum for 20% gate opening

In the case of 40% gate opening condition, again 5 different points have been considered on the gate structure. In contrast to the previous case, here, the first point has a completely different spectrum. Figure 20 and figure 30 show point1 and four other points' power spectrum, respectively.

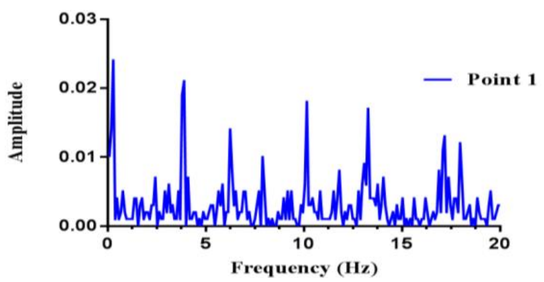

Figure 20. hydrodynamic pressure power spectrum for point1 in case of 40% gate opening

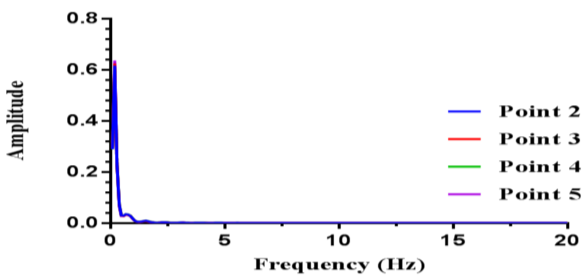

Figure 21. hydrodynamic pressure power spectrum for 40% gate opening except point1

Point 1 shows more frequency contents because it is located just in the edge of the gate, so pressure in this point has more fluctuations.

7. CONCLUSIONS

In the present research, the Flow Characteristics were investigated in the vicinity of Seymareh dam's bottom outlet service gate at various gate openings. The results of the study showed:

1. By moving towards the downstream conduit, due to the reduction of cross section to the service gate, the flow velocity increases and the pressure reduces, and for less gate openings, velocity of the flow at the upstream of service gate gradually increases, but in gate location, it has a sudden increase.
2. The large service gate openings influence the profiles of velocity and pressure more than the upstream of the gate.
3. The cavitation index at the bed of the conduit for the 10, 20, 30, 40 and 80% of service gate from the 41m section to the end and for the 50 and 70% of gate openings from the 41m to 43m section is less than the critical value (0.2).
4. On the wall of the conduit, cavitation starts from the bottom of the gate and the damage continues to the end of the conduit; and for more gate openings, cavitation occurs at the end of the conduit. And also, for the conduit's ceiling the amount of this phenomenon is not closed to the critical value.
5. The frequency of 20% gate opening shows that the power of hydrodynamic pressure for 5 different points have similar frequencies; and for the 40% gate opening point 1 since it has located at the edge of the gate, it has more frequency contents than the other 4 points.

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