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Numerical simulation of bottom outlet valve openings and reverse slope transition to control downstream pressure drop in pipeline of effluent discharge to sea

Saeed Madadyari[1], Mehdi Nezhadnaderi[2]*, Babak Fazli Malidareh[3]

[1]*Department of Civil Engineering, Na.C., Islamic Azad University, Najafabad, Iran; 2219791505@iau.ir*
[2*] *Associate Professor, Department of Civil Engineering, To.C., Islamic Azad University, Tonekabon, Iran. (Corresponding Author); mehdi.nezhadnaderi@iau.ac.ir*
[3] *Associate Professor, Department of Civil Engineering, BaB.C., Islamic Azad University, Babol, Iran; fazli.babak@iau.ac.ir*

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ABSTRACT

Bottom outlets are a set of structures used to transfer water from the dam reservoir to the downstream. Therefore, due to the importance of this part of the dam, the study of the cavitation phenomenon is particularly sensitive. In the downstream bottom outlets, the flow is transferred at high speed, and due to the separation of the flow and its sudden transformation from a pressurized state to a free state, a sharp drop in the pressure values downstream of the valve occurs. The flow passing under the valve creates a swirling flow downstream of it, the main characteristic of which is a sharp pressure drop. The drop created is a function of the valve opening, the water head behind the valve, and the geometry of the channel. On the other hand, severe pressure fluctuations cause a decrease in local pressure in that area, and due to the high flow velocity, the potential for cavitation increases. How to minimize the negative pressures created downstream of the valve is one of the important issues that are raised in the case of valves. The negative pressures created will ultimately lead to damage to the downstream structure and the valve itself. Cavitation is one of the most unpleasant hydrodynamic phenomena that occurs as a result of such negative pressures created downstream of the valve. In this paper, the governing equations of flow in the two-dimensional case in the physical model of the bottom outlet of the Narmashir dam were solved using appropriate turbulence models to calculate the flow and turbulence pattern. The pressure values were obtained from the numerical solution and then the pressure values on the bottom outlet and the surface in front of the bottom outlets were investigated for 30, 50, and 80 percent opening. The results show that the pressure values obtained from the numerical model follow a similar pattern as the results of physical model. With greater opening, the pressures on the bottom and top of the bottom outlet decrease. In this study, by installing a reverse slope transition after the valves and a larger diameter pipe after the transition, the negative pressure at the end of the pipe after the valve can be reduced. By opening the valve up to 50%, this negative pressure is reduced and the possibility of wastewater returning to the pipe is reduced. Also, the risk of cavitation due to direct impact of the jet with the seabed is reduced. A very strong jet may cause: sediment erosion, local mud, pollution, bed erosion and damage to benthic habitats near the seabed. Therefore, installing a reverse slope transition and an end pipe with a larger diameter than the transfer pipe can be a good idea to reduce the risk of the jet impacting the seabed.

1. Introduction

In many cases, when floods enter dam reservoirs, muddy flows are created at the bottom of the reservoir. This flow is one of the factors that causes sedimentation and reduces the water capacity of the reservoirs and the useful life of the dams. Opening the lower gates of the dam is the common method of draining these flows and maintaining the useful volume of the reservoir.

Ariaei and Lashkara (2023) evaluated of the effect of the lower discharger on the behavior of the muddy flow entering the Dez dam reservoir [1].

In this research, in order to pass the incoming sediments to the Dez dam reservoir, the construction of a channel to discharge the flow containing sediment was proposed as a remedial solution. Also, the behavior of the muddy flow entering the reservoir of the dam and its effectiveness in passing the sediments were investigated using numerical simulation. First, in order to calibrate the model, the thick flow pattern formed inside the tank was simulated using different models with different wall roughness heights, as well as RNG and LES turbulence models, and the results of depth and flow velocity were compared with field measurements. In the next step, the lower discharge channel was added to the model in the proposed position and the impact of the construction of this discharger on the behavior of the thick flow entering the tank was evaluated. Investigations showed that the amount of sediments released from the dam tank is directly related to the input concentration and the opening percentage of the lower discharger. In such a way that by averaging the results in different input concentrations, the sediment discharge efficiency in openings of 25%, 50% and 100% was calculated as 15.4%, 20.8% and 25.1% respectively. In the following, profiles of the flow velocity in the upstream sections of the discharger were taken in order to evaluate the intensity of mixing and the amount of deviation of the flow lines. In general, as the flow approaches the inlet opening of the discharge valve, the values of the maximum velocity and also the intensity of the mixing of the surrounding fluid into the concentrated flow increase. Also, with the increase in the opening percentage of the valve, the effect of the discharge channel on the deviation and acceleration of the flow lines becomes wider.

Daryaei et al. (2023) investigated of Flow Pattern Changes Caused by Installing Diagonal Plates Upstream of the Lower Discharge Valve Using Numerical Simulation [2].

In the present study, the effect of installing diagonal plates on changes in the flow pattern upstream of the orifice was investigated using the Flow3D numerical model. The variables studied in this study are the width of the plates, the angle of installation of the plates, and the distance from the plates to the orifice. A total of 5 scenarios (considering the control condition (without installation of plates)) were defined for the numerical model. The numerical model was calibrated using experimental results and the RNG turbulence model was selected for simulation. The results showed that installing diagonal plates in front of the orifice led to the creation of vortices and also the development of a low-pressure zone upstream, which led to an increase in the volume of outgoing sediments. Also, reducing the width of the plates, increasing the installation angle and increasing the distance between the plates will lead to a decrease in the intensity of the vortices and a decrease in the area of the low-pressure zone, which reduces the effect of installing diagonal plates to increase the volume of outgoing sediments.

Rasouli et al. (2021) evaluated the effect of the dimensions of the bottom outlet on the amount of sediment behind the dam in pressure leaching by Laboratory investigation [3].

The exploitation of reservoir dams has so far been carried out with an emphasis on the goals of meeting water needs, controlling flood energy, and improving environmental conditions, and the issue of sediment discharge from the dam reservoir has received less attention. In this study, in order to determine a method for improving sediment discharge, a hemispherical structure was tested in front of the bottom outlet. The tests were conducted by building 16 physical models with different gap lengths and widths at four water heights, three hemispherical diameters, and a total of 208 tests. The results of the experiments showed that by installing a half-cylinder structure in front of the lower discharger, the volume of sediment washing increases. In other words, a pair of rotating vortices are created inside the half-cylinder structure on both sides of the central axis of the valve, in which case installing half-cylinders with different diameters increases the volume and length of sediment washing several times compared to the model without a cylinder. So that by increasing the gap height four times, the volume and length of sediment washing increase by 101.3 and 27.2 percent. The results of this study showed that installing half-cylinders with diameters of 12.7, 15.2 and 19.2 will result in an average increase of 587, 732 and 829 percent in the volume of sediment washing, respectively, compared to the model without a cylinder. Also, installing half-cylinders with diameters of 12.7, 15.2, and 19.2 will result in an average increase in sediment washing length of 94, 106, and 111 percent, respectively, compared to the model without a cylinder.

Jamali Roshet and Manafpour (2019) studied numerical of the flow pattern through the bottom outlet of Seymareh dam [4].
bottom outlet, as one of the hydraulic structures dependent on the dam, have the important task of withdrawing the required water from the reservoir and delivering it to the downstream of the dam. These structures face some problems during operation, such as the occurrence of local eddy currents, severe pressure fluctuations, etc. To identify and deal with these factors, we need a correct understanding of the flow pattern in the channel. In the present study, a numerical study of the flow pattern in the bottom outlet of the Seymareh Dam, in the pressurized and free states, has been carried out using FLOW3D software and the turbulence model (RNG (k-ε)) for different service valve and full emergency valve openings. The results indicate an increase in flow velocity and a decrease in pressure with advancing in the flow direction; so that at full service of valve opening and normal head of 100 meters, the maximum flow velocity was 6.45 m/s and the minimum pressure was 1.4 kPa. In addition, with a gradual decrease in valve opening, the difference in average velocity values and also the bottom pressure immediately upstream and downstream of the valve increases. By comparing the free surface flow profiles, it was observed that the presence of a flow separating ramp at the end of the channel causes an increase in the water level in small valve openings, and with increasing opening, its effect is not significant.

Nemati and Ahmadi (2017) investigated numerical models of the effect of channel curvature before the service gate of the bottom outlet on the hydraulic flow [5].
Bottom outlets are known as lateral hydraulic structures in dams that are responsible for flood control, sediment discharge and flow transfer. In this study, the numerical solution of the flow in a sloping bottom outlet, consisting of multiple geometric sections and with channel curvature before the service gate has been investigated using FLOW-3D software as a computational fluid dynamics (CFD) model. The k–ε model was used as a turbulence model to solve the supercritical flow. The objectives of this paper were to determine and propose a suitable geometric structure of the flow channel to eliminate the downstream swirling flow pattern and to predict the effect of changing the channel geometry on the flow characteristics at the gate location and downstream of the flow. The numerical modeling results were compared with the experimental results. The results showed that by choosing a 25-meter straight length before the gates, the values of turbulence energy and flow pressure after the gates were reduced by 27.86% and 26.17%, respectively.

Manafpour and Jamali Roshet (2016) investigated the possibility of cavitation phenomenon in the bottom outlet of the Seymareh dam [6].

Bottom outlets are used as one of the hydraulic structures of the dam to control the initial water intake of the reservoir, discharge the reservoir in necessary situations, and help with the overflow discharge capacity in floods. By examining damaged bottom outlets in the world, problems caused by cavitation and valve vibration have been identified as the most important causes of bottom outlet failure. In the above phenomena, parameters such as flow velocity, hydrodynamic pressure of water, and flow rate are effective. Increasing the flow velocity in the bottom outlet and subsequently reducing the local pressure leads to a phenomenon called cavitation, which is one of the important and noteworthy issues in bottom outlets. The basic indicator of this evaluation is the cavitation index. It is a function of local pressure and fluid velocity. The critical value of this index is 0.2-0.25 along the channels and 0.2 inside the grooves. For this purpose, the present study investigates the phenomenon of cavitation in the bottom outlet of the Seymour Dam at different service valve openings with the RNG turbulence model using the FLOW3D software, so that if this phenomenon occurs, solutions can be provided to remedy it.

Hosseini Nezhad (2012) studid hydraulic simulation of flow in the bottom outlet of Siazakh dam with FLOW3D software [7].
The bottom outlet of dams is one of the important components of these structures that are exposed to numerous hydraulic problems. Pressure fluctuations are a design consideration for a wide range of hydraulic structures. In addition, the performance of the structure is affected by pressure fluctuations. This phenomenon mainly occurs in hydraulic structures where flow separation occurs at high velocities and low pressures. This research was conducted using Flow-3D software

on the service valve and at different openings of 60, 80, and 100% at three different water heights of 4, 5, and 6 meters in a cylindrical tank. The results obtained from this simulation are consistent with the experimental results. The comparison was made and it is in good agreement. The results show that at lower openings the pressure on the service valve decreases and air injection is a suitable way to solve this problem.

The Narmashir Reservoir Dam is a concrete-core gravel dam that is being constructed 97 km southwest of Bam city on the Narmashir River in Kerman Province to meet downstream water needs. Geographically, the dam is located at latitude 29-30 and 28° and longitude 40-58° and 57°.
The type of dam is a concrete-core gravel dam with a height of 116 meters from the bottom and a crest length of 600 meters. The crest level of the dam is 1465 meters above sea level, the maximum water level in the reservoir is 1465 meters above sea level, and the minimum water level in the reservoir is 1414 meters above sea level.
The type of bottom outlet is an overpass type and the crest level of the bottom outlet is 1460 cubic meters per second. The bottom level of the channel at the gate location is 1364 meters above sea level and the number of gates is 2 service and emergency gates and the type of gate is sliding. The deep bottom outlet consists of a channel with a rectangular cross-section of 2×2.5 and approximately 30 meters long, which is connected to a funnel-shaped opening. Upstream of this opening, there is the main tunnel, at the beginning of which is the dam's inlet intake opening, which is shaped like a funnel. The intake opening leads the flow behind the dam into an elbow, and from there the flow is directed into a 240-meter-long tunnel with a diameter of 6 meters, which ultimately ends at the gates. In the middle of the tunnel, the control system includes a sliding gate and an emergency gate. Downstream of the gates, the flow enters a long tunnel 240 meters long with a circular cross section of 6 meters in diameter (larger than the dimensions of the gate), and therefore the flow downstream of the service gate is assumed to be free.
Due to the high flow velocity in the bottom outlet, which is approximately equal to $V = \sqrt{2gH}$, cavitation, corrosion, and flow aeration are important hydraulic issues in these structures. Therefore, in order to ensure proper performance of the bottom outlet against problems and limitations such as cavitation, hydrodynamic forces, vibration, and structural wear, as well as to examine the ability to completely discharge the tank, the bottom discharger must be carefully designed so that it works well under all desired conditions [8].

2. Methods

In this paper, Gambit software version 16.3.2 is used to generate the geometry and mesh. The mesh pattern is Quad element and map type is used for the surfaces. The existing boundary conditions are velocity input from the left and the pressure output boundary condition is at the outlet from the right. Fluent software uses continuity and Navier-Stokes equations in flow analysis. If the flow is turbulent, then the governing equations are transformed into Reynolds equations and one-equation, two-equation, five- or six-equation models are used to determine the eddy viscosity, with the user specifying the type of model. The flow field is solved based on the separation of equations by the finite volume method and different methods of separation of the transfer terms of the equations such as upstream, second-order upstream, power and Quick can be selected by the user. In order to couple the velocity field and the pressure field, the Simple, Simple C and Piezo methods are available in the program. In this article, Fluent software version 6.3.26 has been used to simulate the flow field.
To solve the flow using computational fluid dynamics, the following steps must be performed (Shojaifard and Noorpour Hashtroodi, 1995) [9].
- Selecting the Gambit model to create the geometry
- Selecting the computational model
- Selecting the calculation solution method in the model
- Selecting the basic equations to solve
- Determining the physical characteristics of the materials
- Determining the boundary conditions
- Specifying the problem solving parameters
- Making an initial guess in the entire solution field
- Performing the solution and outputting the calculations.

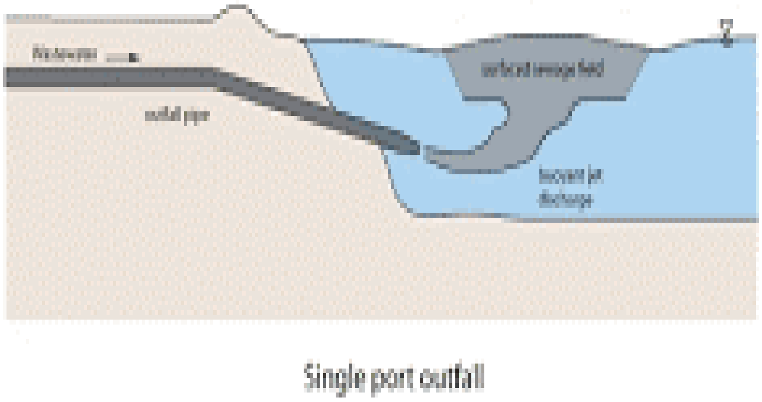

Figure 1- A very strong jet system discharging effluent into the sea may cause: Sediment erosion, Localized siltation, Bed erosion and Damage to benthic habitats near the seabed.

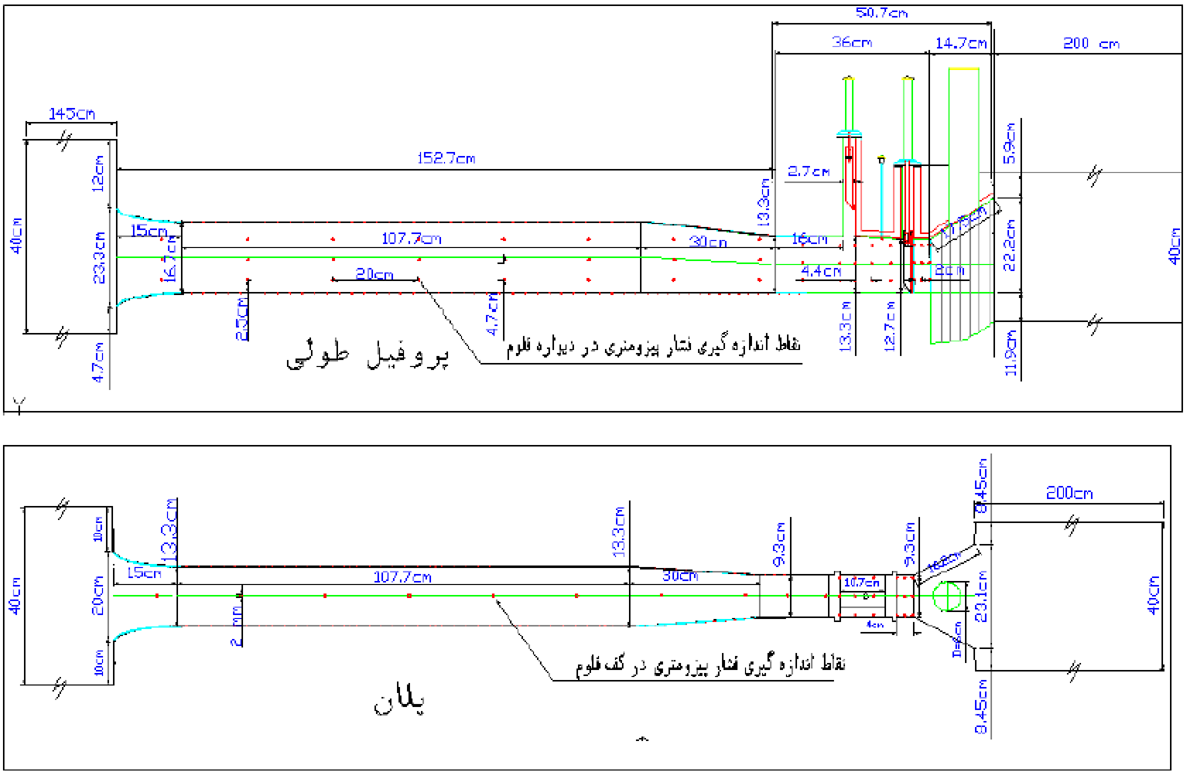

Figure 1- Geometric dimensions of the channel, gates, etc. Physical model of the Narmashir Dam [8].

Table 1 - Horizontal and vertical forces acting on the service valve at normal head (Hosseini et al., 2008) [8].

Service Gate opening	P/γ (top)	P/γ (bottom)	A top	A bottom	Ft (KN)	F_b (KN)	F_{dp} (KN)	F_h (KN)
90	258.4	54.94	0.42	0.448	108.5	241.5	-132.9	1081.0
80	273.11	46.69	0.42	0.448	114.7	205.2	-90.5	1213.0
70	371.7	42.79	0.42	0.448	156.1	188.1	-31.9	1317.3
60	449.69	37.84	0.42	0.448	188.9	166.3	22.6	1619.0
50	493.84	36.34	0.42	0.448	207.4	159.7	47.7	1765.0
40	571.82	38.89	0.42	0.448	240.2	170.9	69.2	1843.0
30	608.61	45.79	0.42	0.448	255.6	201.2	54.4	2020.9
20	661.59	56.14	0.42	0.448	277.9	246.7	31.1	2134.1
10	677.77	73.24	0.42	0.448	284.7	321.9	-37.2	2334.4
5	705.73	83.89	0.42	0.448	296.4	368.7	-72.3	2404.0
2	726.33	91.01	0.42	0.448	305.1	400.0	-94.92	2410.9

3. Results and Discussions

In this study, Gambit software version 3.3.2 was used to generate the geometry and mesh it. The mesh pattern was Quad element and map type was used for the surfaces. The existing boundary conditions are velocity input from the left side from the top of the arc and pressure output boundary condition at the bottom of the arc outlet. The simulation results from Fluent software are seen in Figures 2 to 4.

The first and second stages of the solution process require a geometry and mesh generator. The GAMBIT preprocessor or one of the CAD/CAE software can be used to generate the geometry and mesh. The Tgrid preprocessor can also be used to generate a mesh with volume elements from an existing surface mesh. In the third stage, the two-dimensional FLUENT software must be run.

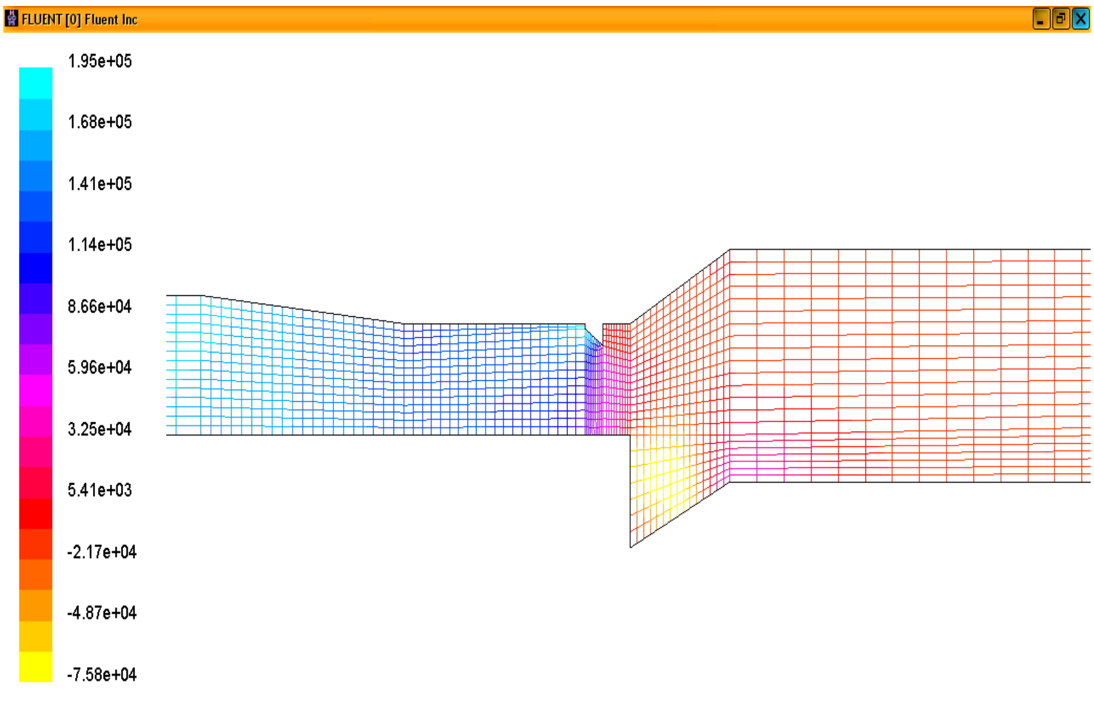

Figure 2- The isopressure curve in Pascals, in the bottom outlet with 80% opening of the lower valve and using the K-ε turbulence model. The results show that the pressure values obtained from the numerical model follow a similar pattern as the results of Hosseini et al. (2008), Table (1). [8].

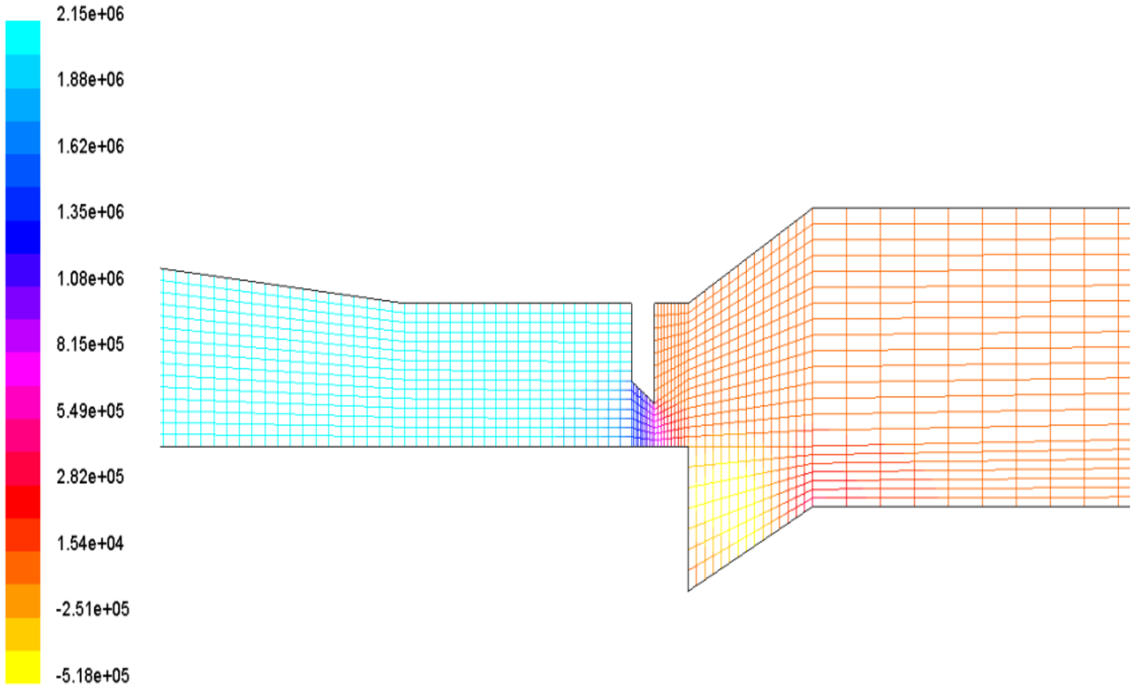

Figure 3- The isopressure curve in Pascals, in the bottom outlet with 30% opening of the lower valve and using the K-ε turbulence model. The results show that the pressure values obtained from the numerical model follow a similar pattern as the results of Hosseini et al. (2008), Table (1). [8].

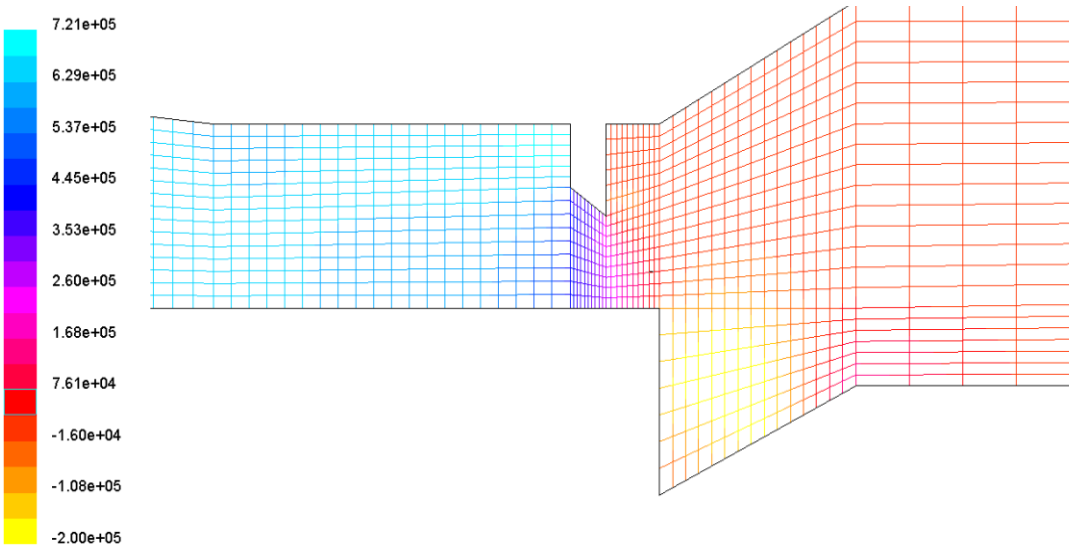

Figure 4- The isopressure curve in Pascals, in the bottom outlet with 50% opening of the lower valve and using the K-ε turbulence model. The results show that the pressure values obtained from the numerical model follow a similar pattern as the results of Hosseini et al. (2008), Table (1). [8].

4. Conclusion

Bottom outlets are structures used to regulate the transfer of water from the dam lake to the downstream discharge point. The present study was conducted to calculate the pressure and velocity at different service gate openings. In this paper, the governing equations of flow in the two-dimensional case in the physical model of the bottom outlet of the Narmashir Dam were solved using appropriate turbulence models to calculate the flow and turbulence pattern. The velocity and pressure values were obtained from the numerical solution and then the pressure values on the bottom outlet and the surface in front of the bottom outlet were investigated for 30, 50, and 80 percent opening. The results show that the pressure values obtained from the numerical model follow a similar pattern as the results of Hosseini et al. (2008). With greater opening, the pressures on the bottom and top of the bottom outlet decrease. Based on the results obtained from the combined operation of the valves, an aerator is required immediately after the emergency valve to prevent cavitation. In this study, by installing a reverse slope transition after the valves and a larger diameter pipe after the transition, the negative pressure at the end of the pipe after the valve can be reduced. By opening the valve up to 50%, this negative pressure is reduced and the possibility of wastewater returning to the pipe is reduced. Also, the risk of cavitation due to direct impact of the jet with the seabed is reduced. A very strong jet may cause: sediment erosion, local mud, pollution, bed erosion and damage to benthic habitats near the seabed. Therefore, installing a reverse slope transition and an end pipe with a larger diameter than the transfer pipe can be a good idea to reduce the risk of the jet impacting the seabed.

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