Detailed vibrational analysis of unbalanced morning glory spillways using coupled finite volume-finite element method

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Received: 3 April 2020 / Accepted: 21 December 2020 / Published online: 11 January 2021
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Abstract

In this research, the structural behavior of a morning glory spillway has been evaluated when there is an unbalanced construction in the spillway crest. The unbalanced construction is defined as the ratio of vertical unbalance in construction to the diameter of the spillway crest. The spillway structure has been modeled using finite element method and the reservoir fluid has been simulated using finite volume method. The behavior of morning glory spillways with unbalanced crests has been investigated in two scenarios: (a) the crest without any anti-vortex structure, and (b) the crest with anti-vortex structures. Both scenarios have been simulated using dynamic linear analysis method. In addition, in each scenario, three amounts of unbalanced constructions of 0.017, 0.035 and 0.052 have been considered. The analysis results have been compared with the structural response of a symmetric spillway without unbalanced construction. Based on the results, the most critical condition occurs during the water flow over the unbalanced spillway with no anti-vortex structure. On the other hand, the presence of anti-vortex piers causes asymmetric flow on the spillway crest and subsequently asymmetric flow pressure at one side of the piers.

Keywords Computational fluid dynamics · Fluid-structure interaction · Morning glory spillway · Finite element method · Finite volume method · Structural dynamics

1 Introduction

Spillways are one of the most important and vital structures in the life of a dam [1]. The efficiency and proper functioning of such structures requires a precise and reliable design. Among different spillways, the morning-glory spillways are standing structures inside the dam reservoir that have a great deal of importance in functionality of the dam [2]. The continuous weight and hydrodynamic loading on the body of spillway concrete structure during a flood complicates the interaction analysis of the structure and the fluid. The behavior of these spillways during over flow can be predicted well using a fluid-structure

interaction analysis with coupled computational fluid dynamics and structural analysis [3].

Cassidy was the first one who applied numerical method for investigating the response of morning glory spillways [4]. He modeled the effect of water depth and static pressure on the spillway crest in a two-dimensional (2D) model, and reported a good compatibility between the numerical results with actual values. Maynard conducted a lot of studies on the shape and height of the morning glory spillway [5]. Betts applied the finite element method to solve the governing equations of the fluid domain, and simulated flow around the spillway [6]. In addition to proper estimation accuracy, he proposed a method to increase the convergence rate of the numerical

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results. Li et al. used the 2D finite element method, and calculated the free surface curvature of the water on a morning glory spillway crest [7]. Olsen and Kjellesvig solved the Navier–Stokes RANS equations with the K -epsilon (K - ϵ) turbulence model in three dimensions, and calculated the discharge coefficient for different types of morning glory spillways [8]. In all the above mentioned studies, Navier–Stokes equations are solved for the fluid domain. However, an efficient RANS turbulence mathematical model should be selected to solve these equations properly. Mainly, single-equation turbulence models, such as the Spalart–Allmaras or two-equation models, such as K - ϵ or K - ω models, have been extracted based on Boussinesq's hypothesis [9, 10]. Boussinesq's hypothesis explains how to estimate the components of fluid stress tensor for the above-mentioned turbulence equations [11, 12]. Based on the simplified Boussinesq hypothesis, the anisotropic turbulence is limited to specific regions. Therefore, this hypothesis is far away from reality due to the anisotropic nature of the turbulence in nature [13]. Among the turbulence mathematical models, the Reynolds stress turbulence model, using six separate transport equations for each of fluid stress tensor components, can effectively analyze an anisotropic turbulence [14]. Such analysis is more accurate and more compatible with reality than the simplified models. In a verification study, Mirabi and Mansoori investigated different turbulent models and showed the high accuracy of Reynolds stress turbulence model in simulating submerged jets with the influence of walls [15]. They suggested that the compressive strain term and the turbulent kinetic energy dissipation term in the Reynolds stress turbulence equation can be estimated precisely.

In addition to the fluid domain, interaction between structures and fluid is another important parameter in modeling the behavior of any structure surrounded by water, such as morning glory spillway. Hou et al. classified different interaction methods based on their accuracy in predicting the behavior of structure and incompressible fluid [16]. In another study, Grandmont and Maday investigated various techniques around structure and fluid interaction [17]. They examined fluid behavior with rigid and elastic structures. The slimy fluid was also used in both compressible and incompressible conditions. Finally, they evaluated the resulting time series, containing different stresses in the structure displacement. Liaw and Chopra assessed the effect of reservoir water interaction on the dynamic response of a basin tower [18]. They applied the dynamic earthquake load and neglected the effect of water surface waves. The fluid was considered as incompressible, and an added mass method was utilized to model the reservoir water. Their results indicated that the interaction analysis reduces the frequency of the basin structure and its modal damping ratio. Goyal and Chopra

tried to investigate the effect of earthquake on the basin towers using the water-structure-soil interaction [19]. The results indicated that this type of modeling is very effective in raising the accuracy of the simulation response. Razavi and Ahmadi simulated a morning glory spillway in three-dimensional (3D) with the Flow3D software [20]. They investigated the accuracy of flow behavior modeling and overflow discharge coefficient and found that simulation accuracy is acceptable in comparison with the existing experimental results. Seo et al. modeled medium size spillways using 3D simulations and investigated the discharge coefficient of flow in various forms of spillways [21]. They showed that the dam labyrinth spillway discharge would be 71% higher than the linear ogee spillway. They also found that the level of the bottom of the lateral channel of the flood discharge is the most effective parameter in flood discharge. Enjilzadeh and Nohani simulated flow on a morning glory spillway [22]. Comparison of the simulation results and experimental data showed that the errors of the estimated discharge and the estimated depth on the spillway crest were about 6.4% and 7.6%, respectively.

The possibility of geometric symmetry error in large structures such as morning glory spillways depends on the current construction technology. The lack of proper technology, or imperfect accuracy of the available devices may cause construction errors (or unbalance construction). Although any asymmetric construction of morning glory crest can affect the flow pattern and subsequently the structural response of the spillway, no comprehensive study has been done to investigate the unbalanced construction of spillway crest. Therefore, in the present study, flow pattern and structural response of a morning glory spillway with unbalanced construction are studied by means of a coupled fluid-structure model. The unbalanced construction is defined as the ratio of vertical unbalance in construction to the diameter of the spillway crest. The maximum stresses in the crest and the throat of the unbalanced spillway are investigated in comparison with a symmetric spillway. Dynamic equations of Newton's second law and turbulent Navier–Stokes with the Reynolds stress turbulence model are used for interaction analysis. The fluid-structure interaction is carried out by combining the finite element and the finite volume methods. The structure loading is applied by the amount of fluid pressure on the structure wall, and the structure response to this loading is considered in terms of the deformation of the boundary conditions of the fluid domain wall. The results of this two-way interaction were evaluated in a time series dynamic model. In addition, the effects of anti-vortex structures on the results are evaluated considering three amounts of unbalanced construction as 0.017, 0.035 and 0.052. Actually the considered unbalanced construction scenarios correspond to angles 1°, 2°, and 3° with respect

to the horizontal line. Finally, the effect of any tolerance in the spillway crest is discussed and the most critical condition during the water flow over the morning glory spillway with and without anti-vortex structure has been determined. The lack of a parametric analysis to reveal the influence of the type, layout and shape of anti-vortex structures on the flow is a limitation of the present study. However, this is an ongoing research and it will be the subject of future publications.

2 Methodology and analysis assumptions

2.1 Governing equations

In order to perform the simulation process, it is necessary to use certain equations to predict the behavior of the structure and the fluid. The equations used for the fluid section are differential equations governing the mass and momentum fluxes of the fluid, and the equations used for the structural part governs the stress and strains of the structural elements. In this research, Reynolds stress turbulence model is used [23]. This turbulence model, with the separate transport of Reynolds stress tensor components, analyzes the anisotropic nature of turbulence. The anisotropic turbulence means that the Reynolds stress tensor components will change under any transformation and rotation. This mathematical turbulence equation is more accurate than turbulence models introduced based on the simplified Boussinesq hypothesis (assuming that the anisotropic turbulence is limited to specific regions). Therefore, the turbulence mathematical equation of the Reynolds stress seven equations is selected as an appropriate option for predicting the random behavior of hydrodynamic parameters of the flow. The governing equations of the RANS type in the fluid domain include the mass transport equation (Eq. 1), momentum (Eq. 2), and turbulence kinetic energy (Eqs. 3 and 4) as [24]:

$$\frac{\partial(\rho)}{\partial t} + \frac{\partial(\rho \bar{u}_j)}{\partial x_j} = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial(\rho \bar{u}_i)}{\partial t} + \frac{\partial(\rho \bar{u}_i \bar{u}_j)}{\partial x_j} = & -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right) \\ & + \frac{\partial(-\rho \bar{u}'_i \bar{u}'_j)}{\partial x_j} \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial(\rho \bar{u}'_i \bar{u}'_j)}{\partial t} + \frac{\partial(\rho \bar{u}'_k \bar{u}'_i \bar{u}'_j)}{\partial x_k} = & -\frac{\partial}{\partial x_k} \left(\rho \bar{u}'_i \bar{u}'_j \bar{u}'_k + p(\delta_{kj} \bar{u}'_i + \delta_{ik} \bar{u}'_j) \right) \\ & + \frac{\partial}{\partial x_k} \left(\mu \frac{\partial}{\partial x_k} (\bar{u}'_i \bar{u}'_j) \right) - \rho \left(\bar{u}'_i \bar{u}'_k \frac{\partial \bar{u}_j}{\partial x_k} + \bar{u}'_j \bar{u}'_k \frac{\partial \bar{u}_i}{\partial x_k} \right) \\ & - \rho \beta (g_i \bar{u}'_j \bar{\theta} + g_j \bar{u}'_i \bar{\theta}) + p \left(\frac{\partial \bar{u}'_i}{\partial x_j} + \frac{\partial \bar{u}'_j}{\partial x_i} \right) - 2\mu \frac{\partial \bar{u}'_i}{\partial x_k} \frac{\partial \bar{u}'_j}{\partial x_k} \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho \epsilon \bar{u}_i)}{\partial x_i} = & \frac{\partial}{\partial x_j} \left(\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right) + \frac{1}{2} C_{\epsilon 1} \\ & \left(-2\rho \bar{u}'_i \bar{u}'_k \frac{\partial \bar{u}_i}{\partial x_k} - C_{\epsilon 3} \rho \beta (g_i \bar{u}'_i \bar{\theta} + g_i \bar{u}'_i \bar{\theta}) \right) \\ & - \rho C_{\epsilon 2} \frac{\epsilon^2}{k} \end{aligned} \quad (4)$$

where u_i is the components of the flow velocity vector, p is the flow's static pressure, $u'_i u'_j$ is the Reynolds stress tensor components, and ϵ is the turbulence kinetic energy dissipation rate. Also, the values of $C_{\epsilon 1}$, $C_{\epsilon 2}$ and σ_ϵ are assumed to be 1.44, 1.92 and 1, respectively [25]. The value of $C_{\epsilon 3}$ is a function of fluid velocity. The above equations are applied to each control volume in three directions, and unknown hydrodynamic components such as static pressure, six components of the Reynolds stress tensor and turbulence energy dissipation rates are derived based on these equations. Standard wall functions are used to model the flow in the vicinity of the wall and a no-slip boundary condition is applied on the walls boundary. The finite volume method is used to discrete these equations in the fluid domain.

For the structural analysis, the governing equation is actually the equilibrium dynamics equation based on Newton's second law as:

$$\{F^{load}(t)\} = [M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} \quad (5)$$

This equation is used for all elements of the morning glory spillway and the displacement (x), velocity ($\dot{x}$) and acceleration ($\ddot{x}$) are calculated as a function of applied force (F^{load}). The morning glory spillway geometry elements are tetrahedron, so it is necessary that the tetrahedron elemental form function is used. As the displacement matrix of each element is determined, the elements stresses can be calculated by:

$$\{\sigma(t)\} = [D]\{\epsilon^{ela}(t)\} \quad (6)$$

$$\{\epsilon^{ela}(t)\} = [B]\{x(t)\} \quad (7)$$

In the above equations, $[M]$ is the structure's mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $[D]$ is the elasticity matrix, and $[B]$ is the strain-displacement matrix, defined as:

$$[M] = \rho \int_{vol} [N]^T [N] dV \quad (8)$$

$$[C] = \alpha[M] + \beta[K] \quad (9)$$

$$[K] = \int_{vol} [B]^T [D] [B] dV \quad (10)$$

where $[N]$ is the shape function matrix. In addition, α and β are coefficients proportional to the mass and stiffness matrix, respectively. To damp the energy generated in the morning glory spillway's concrete structure, 5% critical damping is considered. The damping is considered by the Rayleigh method and with respect to the values of α and β in the structure analysis.

The configuration of the governing equations on the structural part is analyzed by the finite element method. All known matrices are written for all of elements, and then unknown matrices, which include their displacement, are obtained by mathematical methods. The unknown elements obtained by the location and then elements botching in the vicinity of each other, indicate the general and final deformation of the morning glory spillway structure. All normal stresses can be calculated according to the material elasticity used in the structure. Deformation of the structure boundary changes the boundary of the fluid region too and generates new hydrodynamic pressure on the tetrahedron element. Now, this pressure calculated with Eq. (2) should be applied as loading on structural element. To do this, the mentioned pressure, in the form of force applied to the nodes of the structure, is introduced into Eq. (5) as F^{load} . Then, by solving the Eqs. (5) to (10), the structure deformation is calculated, and this deformation is introduced as dynamic mesh in the fluid domain. Again, the fluid in response to this deformation of the dynamic mesh causes another hydraulic pressure on the wall boundary of the morning glory spillway and the above steps are repeated. In this way, the dynamic interaction of structure and fluid is performed bilaterally and the structure can be analyzed given the interaction.

2.2 Geometric and physical characteristics of the numerical model

The crest and throat structure of a concrete morning glory spillway are investigated using 3D simulations with ANSYS software. The cross section of the morning glory spillway structure is shown in Fig. 1. The shape of the crest and the throat sections are designed according to the criteria of the USBR code for design of small dams [26]. The total height of the structure is 50 m and its thickness at the

Fig. 1 Dimensions of crest, throat and the body of the standard morning glory spillway

Fig. 2 3D geometry of morning glory spillways with unbalanced construction of 0.017, 0.035 and 0.052, respectively from left to right (two lines are also plotted to show asymmetric amount), Up: without anti-vortex structure; Down: With anti-vortex structure

crest and base is 3.8 m and 1.0 m, respectively. Figure 2 shows the different types of asymmetric geometries considered to analyze the morning glory spillway structure with the finite element method. Tetrahedron element type is selected and the total number of elements used in partitioning the spillway structure is 7860.

Since the morning glory spillway is made of reinforced concrete the amount of elastic modulus, the tensile and compressive strength of the concrete has been increased in the linear analysis to take implicitly into account the presence of steel reinforcements. Therefore, the physical characteristics of the morning glory spillway concrete i.e. Poisson's ratio and the modulus of elasticity are introduced

as 0.18 and 30 GPa, respectively. Increasing these values was simply to model the structure in the linear range and equivalent of reinforced concrete. The bottom wall has been fixed to the ground support. The Reynolds stress turbulence model is able to model any rapid strain change in various directions due to the applied pressures (pressure strain term). Regarding this, such strains can act like an impact load on the spillway structure. To be compatible with reality, it is necessary to consider such strains by means of the Reynolds stress turbulence model.

The fluid domain is also divided into limited control volumes with the same kind of gridding and tetrahedron elements. The available boundary conditions in the model are the velocity inlet, the pressure inlet, the pressure outlet, the wall boundary and the symmetric boundary conditions. The number of control volumes in the domain is 126220. Because of the presence of curvature in the spillway profile, the grid type is unstructured and the mesh distribution must match in both the domain and structure sections. The reason for this adaptation is a better distribution of the applied pressure by the fluid, as loading, on the structure of morning glory spillway. In order to increase the accuracy of the two-way interaction of the structure and fluid, in addition to the boundary adoptions, the grid density has also been increased. The fluid used in the simulations is water at 20 °C. Therefore, the physical specifications of the standard water at the given temperature are

considered in the models. Figure 3 shows the cross section of the fluid domain.

The flood discharge rate of the spillway is 550 m³/s. Four aeration channels are considered during the throat to prevent the occurrence of a cavitation phenomenon and the unpredictable impact loading caused by the Pitting phenomenon [27]. The above mentioned channels blow air into throat with flow equivalent to 8% of flow discharge. The inlet air stream reduces the impinging jet density into throat and decreases the risk of pressure reduction. The wall roughness is equivalent to 1 mm and the standard wall function is applied to model the flow behavior in the vicinity of the wall boundaries. Exterior boundaries of the model are considered as symmetric boundary condition. By doing this, the velocity gradient at the boundary is zero and the generated waves will not return to the domain. In fact, this state causes the existence of fluid up to a distance away from morning glory spillway structure. At the upper boundary of the domain, atmospheric pressure is established.

3 Results and discussion

As explained, two scenarios have been investigated in this study. The first one is the unbalanced construction of spillway crest structure without anti-vortex structure, and the second one is the unbalanced construction of spillway crest structure with anti-vortex structure. The unbalanced construction is the ratio of vertical unbalance in construction to the diameter of the spillway crest. In both scenarios and under three states of the unbalanced construction as 0.017, 0.035 and 0.052, the dead weight of the structure, the hydrostatic load of the reservoir water, the buoyancy force, and the live load due to the falling motion of the water flow impinging jet over the morning glory spillway has been modeled. Regarding the nature of the problem, the dynamic analysis is done for each scenario. In dynamic analysis, the water flow in the morning glory spillway is modeled by two-way interaction between the structure and the fluid.

3.1 The first scenario (the unbalanced construction of spillway crest structure without anti-vortex structure)

Figure 4 shows the contours of water volume fraction in different stages of flow for different time frames over the morning glory spillway. As depicted in Fig. 4a, 0.017 construction unbalanced construction on structure disrupts the flow symmetric pattern. This asymmetry can be seen in all three different times. Figure 4b displays the unbalanced construction of 0.035. In this situation, the amount

Fig. 3 Gridding of the fluid domain in the vicinity of the morning glory spillway structure

(a) The contour of the volume of fraction of water flow over the morning glory spillway with a 0.017 unbalanced construction (Left: 2 s, Middle: 6 s, Right 10 s).

(b) The Contour of the volume of fraction of water flow over the morning glory spillway with a 0.035 unbalanced construction (Left: 2 s, Middle: 6 s, Right 10 s).

(c) The contour of the volume of fraction of water flow over the morning glory spillway with a 0.052 unbalanced construction (Left: 2 s, Middle: 6 s, Right 10 s).

Fig. 4 Pattern of water flow falling over the morning glory spillway without anti-vortex structure and with the unbalanced constructions over time

of flow asymmetry has been increased. Finally, in Fig. 4c with unbalanced construction of 0.052, the amount of asymmetric flow of water on the morning glory spillway has been increased compared to the two other conditions. With respect to the water flow pattern, relative to the amount of the unbalanced construction, it can be seen that with increasing this value, the symmetry of the flow is disrupted on morning glory spillway and the symmetrical loading equilibrium in the structure is also changed.

Disruption of symmetry and loading equilibrium in different parts of the morning glory spillway causes additional stresses on the structure. Figures 5 and 6 show the maximum tensile stress and the maximum compressive stress caused by the unbalanced construction in the spillway structure during the simulation. As it is known, increasing the amount of the unbalanced construction magnifies the maximum tensile and compression stresses. With regard to the stresses described in Figs. 5 and 6, the maximum tensile stress occurring in the morning glory

spillway wall is 12.1 MPa. Also, the maximum compression stress available in the spillway wall is 10.6 MPa. All of these stresses occur entirely in the structure with the unbalanced construction of 0.052. It is necessary to explain that the linear behavior of concrete is considered to examine the growth of stresses. By doing so, the effects of reducing the structure strength in the event of cracking do not disrupt the calculation. Therefore, the growth and increase of tensile and compressive stresses can increase the possibility of cracks in the spillway body.

Figure 7 shows the point oscillatory displacement on the spillway crest. As it is shown, with increasing the unbalanced construction, the amount of displacement on the upper part of the spillway structure has also been increased. In addition, the oscillatory motion of the morning glory spillway due to the asymmetric and oscillatory loading can cause cyclic loading and fatigue phenomena in the structure. According to Fig. 7, the maximum

Fig. 5 Maximum tensile stresses in the morning glory spillway structure under various unbalanced constructions

Fig. 6 Maximum compressive stresses in the morning glory spillway structure under various unbalanced constructions

Fig. 7 Oscillation displacement chart of a point on the morning glory spillway crest under different unbalanced constructions

displacement of the structure due to the unbalanced construction is about 1.7 cm.

It should be noted that the frequency of the oscillations is about 1 Hz, and the first oscillation mode of the spillway structure is about 0.84 Hz, with participation of 75% of the total mass of the morning glory spillway. Therefore, in addition to the fatigue phenomenon, resonance can also threaten the unbalanced structures with increasing the internal stresses. In addition, the value of imperfection has a great influence on the maximum displacement of the spillway. It can be seen in Fig. 7 that in small imperfection values, the maximum response of the structure has been nearly increased linearly versus unbalanced construction. However, this increasing rate has been clearly magnified for larger imperfection values. Therefore, it is important to avoid any possible imperfection during the construction of a morning glory spillway.

Considering that in addition to the structural weight load and the hydrostatic load of the reservoir, the load caused by the water impinging jet on the crest and the throat of spillway is considered as loading, the oscillations resulting from the existing turbulence will affect the loading system. Therefore, the oscillations caused by the turbulence of the flow should be applied too. This is done by using the turbulence model used to predict the flow behavior. The resulting turbulence is created by the turbulent kinetic energy generation term and expands through the flow molecular and dynamic diffusion terms. The Reynolds stress tensor components also create anisotropic stress oscillations in the model domain. These oscillations appear in the form of time variations of hydrodynamic parameters such as pressure. These changes in the pressure cause time variations in the load, and it changes the state of the stresses of the spillway structure at any given time. One of the most important terms in the Reynolds stress turbulence transport equation is the pressure strain term. This term transports the oscillatory pressure

in a direction to another coordinate direction and, as happens in nature, models the flow. Due to the high velocity flow, when water falls within the spillway, oscillations applied to the structure are significant. These oscillations appear in the form of turbulent kinetic energy. Figures 8 and 9 show the maximum tensile and compressive stresses distribution. In fact, these stresses are the maximum tensile and compressive stresses shown in Figs. 5 and 6.

According to these figures, the maximum tensile and compressive stresses are created in the parts near the fixed support. The maximum tensile stress in the unbalanced construction of 0.052 is 12.1 MPa, and the maximum compressive stress caused by this unbalanced construction is 10.6 MPa. The location of the maximum tensile stresses is the fix support adjacent the outer wall and also the location of the maximum compressive stresses is the fix support adjacent the interior wall. This amount of tension is mainly more than the general tensile strength of concrete and can lead to cracking problems. Due to the submergence of the spillway structure, there is the possibility of water leakage inside the cracks. This may lead to a crack growth and a progressive failure inside the spillway body and eventually its fail.

3.2 The second scenario (unbalanced construction of spillway crest structure with anti-vortex structure)

In this section, anti-vortex structures are designed to prevent the formation of vortex flows in the crest of the morning glory spillway. For this purpose, 4 piers are designed considering the flood flow and the flow depth formed on the spillway crest and they are included in the crest structure. Similar flow conditions as the previous section is simulated with the same boundary conditions. Figure 10 shows the water volume fraction contour in different stages of flow falling over a morning glory spillway equipped with the anti-vortex structure. Like the previous

Fig. 8 The maximum tensile stress distribution (Pascal) contours created in Fig. 5, under unbalanced constructions from left to right, 0.017, 0.035, and 0.052

Fig. 9 The maximum compressive stress distribution (Pascal) contours created in Fig. 5, under unbalanced constructions from left to right, 0.017, 0.035, and 0.052

scenario, in this scenario, Fig. 10a, the unbalanced construction of 0.017, disrupts the flow falling symmetric pattern. Clearly, the asymmetry is visible in all three times displayed. Figure 10b and c illustrates the unbalanced construction of 0.035 and 0.052, respectively. As indicated in Fig. 10c, the amount of asymmetry of the water falling jet over the spillway with the maximum imperfection is more

significant compared to the previous two states. As in the first scenario, it can be seen that with increasing this value, the symmetry of flow falling over the morning glory spillway is disrupted and the symmetrical loading equilibrium in the structure is also changed. According to Fig. 10, during the asymmetric motion of a water falling jet, a portion of the flow at the side of the unbalanced construction is

(a) The contour of the volume fraction of water flow over the morning glory spillway with a 0.017 unbalanced construction (Left: 2 s, Middle: 6 s, Right 10 s)

(b) The Contour of the volume fraction of water flow over the morning glory spillway with a 0.035 unbalanced construction (Left: 2 s, Middle: 6 s, Right 10 s)

(c) The contour of the volume fraction of water flow over the morning glory spillway with a 0.052 unbalanced construction (Left: 2 s, Middle: 6 s, Right 10 s)

Fig. 10 Water flow falling pattern over the morning glory spillway equipped with anti-vortex structure despite the unbalanced constructions in construction over time

first entered into the spillway. This asymmetric jet entry will increase the depth and flow velocity than the opposite side and will generate additional unbalanced forces.

The existence of anti-vortex structure in the spillway crest causes high pressure on the side of anti-vortex wall with unbalanced construction. Therefore, it is expected that the force exerted by this pressure, as a new loading, change the behavior of the structure. Figures 11 and 12 show the maximum tensile stress and maximum compressive stress induced in the structure for different unbalanced constructions. The maximum tensile stress occurs in the unbalanced construction of 0.052 and it is equal to 7 MPa. According to Fig. 12, the maximum compressive stress in a symmetric crest condition (without any unbalanced construction) occurs as 7.3 MPa. It can be seen that the maximum tensile and compressive stresses have been decreased compared to the first scenario. As shown in Fig. 12, the maximum compressive stresses in the morning glory spillway structure in all three cases with 0.017, 0.035 and 0.052 imperfections have been reduced than the no imperfection structure. This suggests that a disincentive factor don't allow that the structure tolerate extreme compressive stress.

However, the tensile stress in the structure has been increased compared to the no imperfection model. It is clear that the force reduces the structure's motion in order to increase the compressive stress and the torque resulting from the eccentricity adds some to tensile stress. For morning glory spillway structure, the compressive stress in fixed support increases when the displacement of the structure increases on the unbalanced construction side. But, Fig. 11 shows that the mentioned factor causes the structure to experience less tensile stress than the first scenario, which is a good point in preventing structural failure.

Figure 13 shows the oscillatory displacement of a point on the morning glory spillway crest with anti-vortex structure. It is clear that the amplitude of displacement and oscillations of the spillway structure have been reduced than the first scenario. Considering the above discussions about the tensile and compressive stresses for the present scenario, the structure response indicates that there is an oscillation deterrent factor with high amplitudes. The oscillation frequency of the structure in all three modes of unbalanced construction is approximately 1 Hz, but according to Fig. 13, the oscillations than the frequency

Fig. 11 Maximum tensile stresses in the morning glory spillway structure equipped with anti-vortex structures with different unbalanced constructions

Fig. 12 Maximum compressive stresses in the morning glory spillway structure equipped with anti-vortex structures with different unbalanced constructions

Fig. 13 Oscillation displacement diagram of a point on the morning glory spillway crest equipped with anti-vortex structure under various unbalanced constructions

of the intact structure have a phase difference. The phase difference, decrease of amplitude of oscillations and decrease in the intensity of maximum tensile and compressive stresses indicate the effect of anti-vortex structure as a stress-balancing agent. Large dimensions of the anti-vortex structure, as well as the asymmetric depth and velocity of water impinging jet increase the dynamic pressure on one side of the structure and it, like a balancing force on the crest, prevents the spillway structure from over-distortion.

Due to the flow turbulence, there is always an oscillatory load in the morning glory spillway structure. As shown in Fig. 13, these pressure oscillations cause oscillating movement of spillway structures even for a structure with no inclination. In other words, the pressure oscillations within the turbulent flow are calculated based on the existing turbulence phenomenon and it is applied as an oscillatory load to the structural walls. In the dynamic analysis of the structure, the spillway responds to the oscillatory load considering the inertial forces and a cyclic increasing and decreasing stresses will be generated. This mode may create a fatigue phenomenon for the structure. The dimensions of the small and large swirling structures (Eddy) caused by such oscillations are directly dependent on the dimensions of the duct and the Kolmogorov scale. This means that in the case of changing the dimensions of the spillway, the amount of turbulent kinetic energy budget will change. Therefore, the main cause of oscillatory motion in small amplitudes is oscillations resulting from turbulence of the flow. The existence of energy dissipation term in the transport equation of turbulence causes the oscillatory kinetic energy to be converted to heat when the Eddies reach the Kolmogorov microscales. As a result, the amplitude slows down gradually over time. Figure 14 shows the distribution of the static pressure contour due to the movement of water impinging jet on the anti-vortex structure. As shown in this figure, the amount of total pressure applied to the wall of the

anti-vortex structure is significant in all cases. Due to the area of the walls and the pressure contour, considerable force is applied to the structure in order to maintain balance. This force, like a deterrent factor, prevents the oscillation of large-scale spillway structure and subsequently minimizes undesirable tension and compression stresses. This effect is quite evident by comparing the results of second scenario (in Figs. 11, 12, and 13) in comparison with the results of the first scenario. According to Fig. 14b (unbalanced construction of 0.035), the amount of pressure distribution on the anti-vortex structure is greater than that is in Fig. 14a (unbalanced construction of 0.017) and Fig. 14c (unbalanced construction of 0.052). Therefore, the force applied to the structure should also be greater than two other cases. This is evident in Figs. 11 and 12 in the form of maximum tension and compression stresses compared to the 0.017 and 0.052 unbalanced constructions. Also, according to Fig. 13, the displacement and amplitude of the oscillation of the structure in the unbalanced construction of 0.035 is less than the values for unbalanced construction of 0.017 and 0.052.

Figures 15 and 16 show the maximum tensile and compressive stress distribution contours of the morning glory spillway structure equipped with the anti-vortex structures. The above mentioned stresses are the maximum compressive and tensile stresses shown in Figs. 11 and 12, respectively. According to Figs. 15 and 16, the maximum tensile and compressive stresses, such as the first scenario, are formed in the parts near the fixed support. The maximum tensile stress in the unbalanced construction of 0.052 is 7.06 MPa, and the maximum compressive stress caused by the unbalanced construction of 0.017 is 7.14 MPa. The location of maximum tensile stresses is in the fix support adjacent outer wall and also the location of the maximum compressive stresses is the fix support adjacent interior wall.

(a) Distribution of the hydrodynamic pressure (Pascal) on the anti-vortex structure located on the morning glory spillway crest with unbalanced construction of 0.017.

(b) Distribution of the hydrodynamic pressure (Pascal) on the anti-vortex structure located on the morning glory spillway crest with unbalanced construction of 0.035

(c) Distribution of the hydrodynamic pressure (Pascal) on the anti-vortex structure located on the morning glory spillway crest with unbalanced construction of 0.052

Fig. 14 Static pressure distribution contour (Pascal), in the three different times shown in Fig. 10

Fig. 15 Maximum tensile stresses contours (Pascal) created in Fig. 11 (equipped with anti-vortex structures), under unbalanced constructions, from left to right 0.017, 0.035 and 0.052, respectively

Fig. 16 Maximum compressive stresses contours (Pascal) created in Fig. 11 (equipped with anti-vortex structures), under unbalanced constructions, from left to right 0.017, 0.035 and 0.052, respectively

4 Conclusions

In this study, the dynamic structural response of the morning glory spillway is investigated via coupled

fluid-structure numerical model. Three possible unbalanced constructions of spillway as 0.017, 0.035, and 0.052 are studied in two scenarios. The first scenario is the unbalanced construction of spillway crest structure without anti-vortex structure, and the second one is the unbalanced

construction of spillway crest structure with anti-vortex structure. The combination of the finite volume method for the fluid domain and the finite element method for the structural part is utilized to simulate two-way interaction. The loading on the structure is applied through the fluid pressure, and the structure response to this loading is considered as the deformation of the boundary conditions of the spillway wall, on the fluid domain. For the fluid part, the Reynolds anisotropic stress turbulence model has been solved. The purpose of using this turbulence equation, in addition to its proper accuracy, is its ability in estimating the rapid pressure strain in different coordinate directions. Therefore, the structure loading is much closer to what happens in reality during water jet flow through the spillway.

The results of the analysis show that the most critical condition in creating the maximum tensile stress (12.1 MPa) occurs in the first scenario, that is, the morning glory spillway with no anti-vortex structure. In addition, the maximum compressive stress (10.6 MPa) occurs in this scenario too. In both scenarios, creating a cyclic loading for the morning glory spillway structure will cause additional fatigue-induced tensions that can affect the structure. Due to the presence of anti-vortex structure on the morning glory spillway crest in the second scenario, the water impinging jet causes a significant pressure on the anti-vortex walls. The mentioned pressure is due to the asymmetric flow of water from one side and its impact on the wall of the anti-vortex structure. This pressure results in a deterrent force from the over-displacement of the morning glory spillway crest along unbalanced construction and reduces the maximum tensile and compressive stresses compared to the first scenario. On the other hand, it is concluded that if no anti-vortex structure is applied, the structural stresses will be increased significantly by raising the crest inclinations. However, in the case of using anti-vortex structures, most of the unbalanced forces will be absorbed by anti-vortex structures and smaller stresses will be generated in the spillway structure. According to the results of the analysis, the 5% damping of the structure and the turbulent kinetic energy dissipation term gradually dissipate the oscillatory amplitude of the structure.

It is concluded finally that the construction of the anti-vortex structures on the morning glory spillway crest can efficiently reduce the maximum tensile and compressive stresses caused by the unbalanced construction. On the other hand, by using the anti-vortex structures the maximum structural stresses will be less sensible to the crest imperfection. It is clear that the dimensions of spillway and its location in the reservoir can affect the performance of a morning glory spillway structure equipped with an anti-vortex structure. Therefore, to introduce an optimum anti-vortex structure, in addition to spillway conditions, it is

necessary to study other parameters such as number and dimensions of anti-vortex structures versus different flow conditions with probable cavity problem.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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