Simulation of Downpull Forces of Leaf Gate in High Dams

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ABSTRACT
The downpull forces on high head leaf gates due to underflow conditions are of paramount importance in the design of gate hoist, especially during opening and closing operation. Hence, there is a need to enrich the concept of estimating the hydrodynamic forces caused by the deflection of streamlines along the bottom side of the gate. In this research, bottom downpull force coefficient of leaf gate in high dams was estimated by the solution of two dimensional Navier-Stokes equations using standard k-ε turbulence model. The equations were solved by ANSYS FLUENT software using finite volume techniques. Experimental investigations in the hydraulic laboratory in College of Engineering/ University of Salahaddin were also conducted so as to calibrate and verify the numerical results. The evaluated model was used to predict the distributions of the piezometric head on the inclined gate lip surface, top and bottom tunnel walls, and predict the distributions of bottom downpull coefficient in the gate lip considering the effects of many geometric and hydraulic parameters.

INTRODUCTION
Vertical lift gates are among the most widely used high head gates for flow regulation or emergency closure of large outlets and conduit. One case of gates is the tunnel-leaf gate which goes through a gate shaft located within the tunnel conduit. Nevertheless, it may be subjected to large downpull forces that are resulting from two military units, one resulting from the flow passing over the top gate surface through the upstream and downstream gate clearances, whereas the other results from pressure exerted on the bottom gate surface by the flow issuing beneath the gate. The resulting pressure difference between the top and bottom induces an unbalanced force which may be in the downwards direction, known as the hydraulic downpull, or in the upward direction termed negative downpull or uplift force. Because of magnitude of downpull force that affects by the design of the gate-hoisting equipment. Its prediction is of major importance to hydraulic engineering and designers. And severe vibration as a consequence of high velocity fluid around the gate lip and low pressure due to suction
induced by high momentum fluid downstream of the control section, (Aydin, 2002).

Many surveys are taken to find the magnitude of downpull and looked into some relevant parameters. A linear figure that can be utilized for estimating downpull force acting on high head leaf gate taking into account the issue of flow parameters and boundary geometry on it, (Naudascher et al, 1964). An experimental model study was directed on a 3-leaf powerhouse intake gate system for TVA'S Melton Hill Dam and conducted to develop a gate design that would effectively shut off the turbine flow for all discharges up to 5700cfs. Tests on five proposed gate lip shapes and on nine other basic shapes failed to produce a satisfactory gate design. The reasons were of excessively large hydraulic force included with the lip forms, oscillation of the gate during closure and, in several of the designs, failure of the leaves to close. The tests finally led to the development of an acceptable design, (Elder and Jack, 1964) (quoted in Al-Kadi, 1997). A model study of hydraulic downpull on a high-leaf gate for powerhouse emergency closure was conducted. The downpull forces were measured while the initial discharge, the gate closure speed, the gate slot head wall geometry, and the bottom shape of the gate were varied. The downpull on the top and bottom beams of the gate with eight bottom shapes and the discharge rating of the gate were presented in a generalized form for use in the design of similar gates. Another result was that a properly designed head wall minimized the downpull on the top seal of the gate, (Smith, 1964) (cited in Al-kadi, 1997).

General studies were made to determine design parameters for hydraulic downpull on downstream seal, roller-mounted gates located in entrance transition of large conduits. Data were presented in both dimensional and non-dimensional form on the effects of gate leaf and gate shaft geometry and on air vent size. The results indicated a maximum downpull force about (710 kips) would occur during the emergency closure of the gates if free discharge conditions occur in the downstream gate frame, (Murray and Simmons, 1966). A random hydraulic model was constructed to investigate the effect of fourteen gate lip shapes on the value of downpull force. The study included the investigation of the effect of the gap width ratio and gate lip geometry on the magnitude of top downpull coefficient. The results indicate that the top downpull coefficient was sensitive to the change in gap width ratio but not changes with gate lip geometry. On the other hand, the bottom downpull coefficient was influenced effectively by the gate lip geometry, (Ahmed, 1999). The effect of downpull on tunnel type-high head gate using a hydraulic model was investigated, According to the tail water conditions free surface flow and submerged flow have occurred, (Drobir et al., 2001).

In the present study, the water flow controlled by leaf gate in dams under high pressure had been modeled using “FLUENT” software to estimate the bottom downpull force coefficient on the gate lip. The model was calibrated and verified using laboratory results.

2.THEORETICAL CONSIDERATIONS
2.1. Hydraulic Downpull Force

The downpull force is influenced by various parameters, which may be classified into three groups, (Sagar, 1978). The first group: The flow characteristics which include the operating head on the gate flow conditions which contain whether free or submerged flow exists and aeration downstream the gate. The second group: Includes the flow properties such as the specific weight of water, dynamic viscosity, and vapor pressure. The third group: Is the geometry of gate installation, including conduit height upstream the gate shaft, gate opening, gate thickness, gate shaft dimensions, angle inclinations of gate bottom with horizontal, geometry of other lip shapes, and
2.2. Bottom Downpull Coefficient

The bottom downpull coefficient can be estimated as follows:

\[ k_b = \frac{H_i - Y_s}{\frac{V_j^2}{2g}} \]  

And \( \frac{V_j^2}{2g} = H_u - Y_s + \frac{V_s^2}{2g} \)

Where: \( H_i \) = Piezometric head at specific points on the bottom surface of gate, \( Y_s \) = Piezometric head downstream the gate at contracted jet, \( V_j \) = Velocity of the contracted jet issuing from underneath the gate, which is obtained from the results of model, \( H_u \) = Piezometric head upstream of the gate, and \( V_s \) = Average velocity of the flow in the conduit upstream the gate, (Naudascher, 1964).

2.3. Governing Equations

2.3.1. The standard K-Epsilon model

The model is based on the solution of two transport equations, namely one equation for the turbulence kinetic energy \( k \) and one for the rate of dissipation of turbulence energy \( \varepsilon \) these equations are solved simultaneously with other governing equations of fluid motion. The standard form of the model is applicable to high Reynolds number flows where the effect of molecular viscosity is negligible. The model also provides good economy and reasonable accuracy for a wide range of turbulence flows, (Lauder and Spalding, 1974).

The equations for \( k \) and \( \varepsilon \) are written as:

**k- Equation**
\[ \rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i} \left( \mu + \mu_t \sigma_k \frac{\partial k}{\partial x_i} \right) + P_k - \rho \varepsilon \]  

**\varepsilon- Equation**
\[ \rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i} \left( \mu + \mu_t \sigma_\varepsilon \frac{\partial \varepsilon}{\partial x_i} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} P_k - C_{2\varepsilon} \frac{\varepsilon^2}{k} \]

Where: \( c_1, c_2, \sigma_k \) and \( \sigma_\varepsilon \) are constants. The term is the generation of turbulence kinetic energy \( k \) due to the interaction between the Reynolds stresses and mean velocity gradients, which can be written as:

\[ P_k = -\rho \bar{u}_i \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} \]  

Since
\[ \tau_{ij} = \mu \varepsilon_{ij} \]  

Where: \( \mu \) = the laminar viscosity and \( \varepsilon_{ij} \) is the rate of strain tensor.

Substituting Eq. (5) into Eq. (4), yields
\[ P_k = \mu_t \left( \frac{\partial \bar{u}_i}{\partial x_j} \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \frac{\partial \bar{u}_i}{\partial x_j} \right) \]

The model uses Eq. (6) to determine the eddy-viscosity(\( \mu_t \)). The standard k-\( \varepsilon \) model employs values for the constants that are arrived at by comprehensive data fitting for a
\[ C_\mu = 0.09; \sigma_k = 1; \sigma_\varepsilon = 1.3; C_{1\varepsilon} = 1.44; C_{2\varepsilon} = 1.92, \text{ (Piradeepan, 2002).} \]

### 2.3.2. Setting Boundary Data for the Present CFD Analysis

Appropriate condition must be specified at domain boundaries depending on the nature of the flow. In the simulation performed in the present study

1. **Inlet boundary**: inlet boundary condition is specified pressure; the distribution of pressure inlet values is taken from experimental study.

2. **Outlet boundaries**: outlet boundary conditions its defined Outlet pressure with a known value.

3. **Wall boundaries**: the solid boundaries of the fluid domain are defined as smooth and non-slip walls. Non-slip wall is the most common type of wall boundary condition implementation, in which the fluid immediately next to the wall assumes the velocity of the wall, which is zero by default (ANSYS Help, 2011). The interior cell zones are defined as a fluid and the faces of gate are taken to be interior wall boundaries, see Fig (3) and (4).

#### 3. Experimental Work and Equipment

The inlet tank was manufactured from Perspex sheets had one tunnel had square cross section 0.2×0.2 m with 1.5m length. The end of the tunnel was provided by a slide gate to control the flow condition. Fifteen piezometric tubes with 6mm diameter were fixed at several locations along the center line of the top and bottom of the tunnel with 5cm interval. Five of them were fixed on the top of the tunnel at a distance 5cm from the downstream face of the gate and the other were fixed in the bottom at a distance 40cm from the upstream end of the tunnel. All piezometric tubes were fixed on the side inlet tank with a metric scale. This tunnel was connected to the inlet tank has 0.86m height with a square cross section bed of 0.61m×0.61m. The gate was manufactured, 5cm thickness, and 20cm width with 45° inclined lip angle. It was located at a distance 0.5m from the tank. Two rows of piezometric tube, with 4mm diameter and 2.5cm away from the center line were fixed on the gate lip. Each row had four piezometers with 12mm interval. The first piezometer was fixed at 6mm from the vertical upstream face of the gate. All piezometers were 12mm apart.

Three pumps were set up near the tunnel to feed the tunnel from the pipe via the inlet tank into the sump tank. Details of the experimental are shown in fig (5) and Photo. (1). the flow rate that passing via the tunnel was measured using volumetric flow rate tank. At the beginning of experiment, both the two gates were closed (model gate and d/s gate). The water started to be circulated by three pumps to feed the tunnel by inlet tank. The gate was opened gradually at a certain height. After a sufficient operating time, in order to gain fully submerged condition, the d/s gate would be gradually opened in order to get constant flow rate. All piezometers were checked to be free of bubbles. The readings were taken for every run from all piezometers. The gate was opening at (y=1 cm, 2cm, 3cm, 4cm, and 5cm).
### 4. RESULTS AND DISCUSSION

#### 4.1. Test the Validity of ANSYS FLUENT Model

Usually any numerical model should be verified using reliable experimental data in order to test the validity of the model for the considered problem. ANSYS-FLUENT program was verified using experimental data that were read in certain positions in flow field.

#### 4.1.1. Piezometric Head Positions Used in the Test

The following three positions were considered for the comparison between experimental and numerical models:

- **Position (Ht)** which indicated the distribution of piezometric head on the downstream top of the tunnel wall.
- **Position (Hb)** which indicated the distribution of piezometric head along the bottom of tunnel wall.
- **Position (Hi)** which indicated the distribution of piezometric heads on the gate lip.

The distribution of piezometric head on top, bottom of the tunnel wall, and along the inclined gate lip surface ($\theta=45^\circ$) were obtained by piezometric tubes used in the model. The readings were plotted and compared with those obtained by ANSYS FLUENT program. Figs. (6 to 10) showed a comparison between numerical and experimental results of piezometric head for different gate opening ratios ($YY/Y_0=5\%, 10\%, 15\%, 20\%, \text{and} 25\%$), where $Y$ was height of the gate opening and $Y_0$ is height of the tunnel. “$x_1$” was a top or bottom distance measured horizontally from the first point of piezometric tubes fixed on the tunnel wall, or “$x_1$” was a distance measured horizontally from the leading edge of the gate lip toward trailing edge of gate, and $d_1$ was total horizontal distance. Figs. (6 to 10) showed good agreement between numerical and measured piezometric head values. The correlation coefficients for the comparison of numerical and experimental piezometric head values showed that the maximum and minimum correlation coefficient ($R$) were 0.9737 and 0.84 at gate opening ratios 20% and 10% respectively.
The bottom down pull coefficient $k_b$ could be computed by Eq. (1):

$$k_b = \frac{H_i - Y_s}{\sqrt{2g}}$$

Where: $(H_i)$ was the local piezometric head at specific points on the bottom surface of gate, $(Y_s)$ was the piezometric head downstream the gate at contracted jet and $(V_j)$ was the mean jet velocity below the gate. The variation of piezometric head along the bottom of gate was presented as non-dimensional term $(k_b)$ plotted versus the distance along the gate thickness $(x/d)$ for various gate opening. “X” was a distance measured horizontally from the leading edge of the gate lip toward trailing edge of gate, and $d$ was the gate thickness. The basic objective of prediction $(k_b)$ at various points along the bottom surface of gate was to understand and analyze the flow pattern under the gate and to correlate it with the fluctuating pressure on the gate bottom. Thus, the observation of the separation and reattachment points along the gate lip were useful in the present investigation due to their importance in describing the behavior of the flow beneath the gate and hence to reveal whether the separated flow from the leading edge of the gate lip would reattach or remain separated from the gate bottom. The location of reattachment zone was indicated by a sudden increase in $(k_b)$ followed by a maximal positive pressure whereas the separation zone could be pointed as a region of low constant pressure head followed by sudden rise in pressure. The fact that $(k_b)$ remains particularly constant over the gate thickness indicates that the flow was completely separated from the gate bottom.

Fig. (8): Comparison between numerical and experimental values of piezometric head for $H_t$, $H_b$ and $H_i$ positions at gate opening ratio $(Y/Y_0=15\%)$

Fig. (9): Comparison between numerical and experimental values of piezometric head for $H_t$, $H_b$ and $H_i$ positions at gate opening ratio $(Y/Y_0=20\%)$

Fig. (10): Comparison between numerical and experimental values of piezometric head for $H_t$, $H_b$ and $H_i$ positions at gate opening ratio $(Y/Y_0=25\%)$

Fig. (11): Comparison between numerical and experimental values of $(k_b)$ for different gate opening ratios
surface, (Reynolds, 1974). The distribution of bottom down pull coefficient along the gate lip surface obtained from Eq.(1) were plotted and compared with those obtained by the ANSYS FLUENT program for different gate opening ratios was shown in Fig (11). Fig (11) revealed good agreement between numerical and experimental values. It means no reattachment appeared in Fig (11) since there is no rapid increase in $k_b$ values. Fig (12) showed the ANSYS FLUENT results of velocity vectors, pressure contours and velocity streamlines for the flow field with opening gate ratio $Y/Y_0 = 5\%$. Fig (12) observed that the maximum velocity reached 2.448 m/s at control gate in the downstream end of the tunnel. Figure (12) also illustrated that the piezometric pressure changed from 7552.9 pa near upstream of the gate to about 6713.8 pa downstream the gate within the gate opening.

5. Conclusions

ANSYS FLUENT V14 was used to estimate the downpull forces on tunnel gates for high dams. Laboratory model was conducted to investigate the bottom downpull coefficient for vertical leaf gate. Several runs were conducted to find the piezometric head distribution and water discharge. The bottom downpull coefficient ($k_b$) was calculated from measurements of piezometric head on the bottom gate surface for different gate opening and for the fully submerged (pressurized) flow condition. The ($k_b$) values obtained from experimental measurements were used to calibrate and verify ANSYS FLUENT program.

The following conclusions can be outlined:

1. The comparison between numerical and experimental results of piezometric head for different gate opening ratios ($Y/Y_0= 5\%, 10\%, 15\%, 20\%, \text{and} 25\%$) showed good agreement between numerical and measured piezometric head values.

2. The comparison between distribution of bottom downpull coefficient along the gate lip surface obtained from experimental value and with those obtained by the ANSYS FLUENT program for different gate opening ratios was shown good agreement between of them.

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