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Examination of the Influence of Cut-off Wall Length on Uplift Forces in Diversion Dams (Case Study: Borj Dam)

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Abstract

The difference in hydraulic head upstream and downstream of the dam, which is subject to hydrostatic pressure, leads to water infiltration through various cracks in the body and structure of the foundation of the diversion dam. Hydrostatic pressure, essentially an upward force acting to reduce the dam's weight, is a primary cause of dam failure. The objective of this research is to find a solution for reducing under-pressure forces and seepage beneath these dams. Reducing uplift force significantly impacts the execution and maintenance costs of a diversion dam. In this research, numerical modeling was conducted by using the finite element method, utilizing SEEP/W software for simulation of the flow through the Borj diversion dam foundation. Various locations of the drain pipe and cut-off were investigated from upstream to downstream beneath the Borj diversion dam foundation. It was observed that 0 degree downstream and 75 degree upstream was suitable for reducing the uplift forces. The 90 degree cutoff wall in the modeling was increased the uplift force result. Under the dam and reducing the uplift force, the angle of execution to the outside, the appropriate angle between 60 and 75 degrees was used.

1. Introduction

Dam construction has a direct impact on the economy, social, and political activities and it is a costly part for governments. Any method of reducing this cost can be considered important in showing the ability of engineers in this sector. Although the cost of construction of diversion dams is far lower than the cost of construction of big dams, the destruction of a diversion dam downstream of the dams practically makes it impossible to use and exploit the regulated water of the dams. One of the forces acting on a dam, which plays a decisive role in the design of the dam, is the uplift force. Various methods have been studied to reduce the destructive factors of this force, including: dam walls, horizontal and vertical drainage, dam blanket, etc.

For dams built on penetrable soil establishment, the water permeates through the soil applying uplift pressures, and may carry soil particles with it driving to weaken disintegration. Hence a dam established on permeable soil has to be designed against uplift forces. This water under the dam exerts pressure in all directions into the voids between

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the soil particles beneath the structure (Hamid Rasool et al., 2021).The most common method to prevent water seepage beneath the dam foundation is the implementation of a cut-off wall (Abbaszadeh Shahri et al., 2011).

The most critical principles in the design and construction of dam structural operations involve the creation of a cut-off wall. The cut-off wall is a structure used as an effective method for reducing the detrimental uplift or under-pressure forces in dam engineering, particularly in diversion dams. The primary role of the cut-off wall is to elongate the flow path of water beneath the dam or diversion structure, which is a crucial factor in reducing under-pressure forces. These under-pressure forces can significantly compromise the dam's safety against overturning and sliding (Huang et al., 2021). Cut-off walls are placed both upstream and downstream of the dam and diversion embankment. Various studies have so far been conducted concerning the change in dimensions of the cut-off wall as a factor in the strength of dam foundations, the impact of location, the depth of cut-off walls, the effect of drainage, the exit gradient from the foundations of diversion dams, and the optimal number of cut-off walls. Both laboratory and numerical investigations were conducted into the performance and positioning of the apron and cut-off walls in reducing the exit gradient in the foundation of diversion dams. In this study, the impact of these two parameters on reducing the exit gradient and controlling piping was examined. The numerical simulation results, which were in alignment with laboratory findings, were presented as the study's outcome. They also reported a simulation error of less than 5% (Ashrafi et al., 2020). Some studies show that this the different seepage reduction systems can reduce flow rate by an average of 83%, seepage rate by an average of 15.5% The water level averages 9.5% downstream of the dam. The results of this study showed that diversity in the type of reduction systems has a significant effect on reducing the flow of the body and its foundation (Roushangar et al., 2023). Some of researchers conducted a study using PLAXIS software to examine the influence of cut-off walls on water seepage rates from the foundation and the uplifting pressure impacting a concrete dam. Their findings showed that enlarging both the thickness and depth of the cut-off wall along the dam's axis led to a decrease in the uplifting force. Notably, the effect of deepening the cut-off wall was more significant than thickening it to reduce this force. By positioning the cut-off wall upstream, the uplifting force was diminished; as the wall was moved further upstream, the distance between flow paths increased, leading to a subsequent decrease in water seepage rates (Angelov & Ahangar Asr, 2021). Wang et al. (2024) explored the simultaneous and synergistic effects of seepage flow and tensile stress on cut-off walls. The results indicated that water pressure was stabilized above the cut-off wall, specifically at the upstream and downstream ends, where cracking might occur. An increase in the depth of the cut-off wall reduced this stress. Additionally, as the water height increased upstream of the dam, the stress exerted on the cut-off wall progressively increased.

There are laboratory investigations to optimize the location of drainage holes for reducing the uplift force in dam foundations. Pressure variations were measured with changes in upstream water level using installed piezometer tubes, and changes in hole location were also assessed. They determined the optimal position for the drainage hole based on minimizing the uplift force. When the ratio of the distance of the drainage hole from the toe of the dam to the dam's length was 0.4, the minimum amount of uplift force was observed. This was attributed to the creation of atmospheric pressure at the location where the drainage hole was embedded beneath the foundation (Salehi et al., 2019).

Water force is one of the main causes of earth dam failure. To deal with seepage Through the foundation of the dam, the construction of cut-off wall is a widely used matter and a Conventional technique (Sazzad & Islam, 2019). Additionally, the same authors and their colleagues (2014) studied the impact of the length of the cut-off wall on reducing uplift forces (Mansuri et al., 2014). Similarly, evaluation of a validation process by comparing numerical results obtained from finite element modeling using SEEP/W software with a previous study specified in hands. This study had been validated for dams with examples in soil mechanics. The numerical model was simulated under the same environment as the case study, which showed a good match, and a selective study was developed to calculate the driving variables and decision variables from different scenarios. Numerical modeling results showed that the cut-off value of the lifting pressure is 25% lower than the value obtained by using the pipe tube (Hassan & Fadhil, 2023). The effect of the different configurations of double-cutoff walls beneath hydraulic structures on uplift forces. The study noted an inverse correlation between uplift forces and the depth of the cut-off wall, with deeper walls resulting in reduced uplift forces (Salmasi et al., 2020). A research study focused on numerical modeling was conducted for the geometric design of the cut-off wall. In their simulations, the cut-off wall's length was consistently set at 12 meters. They concluded that an optimal angle of 70 degrees effectively prevents erosion, while an angle of 90 degrees was found to be most suitable for reducing uplift forces. Another significant finding of the study is the use of a downstream cut-off wall. The research indicates that increasing the depth of the cut-off wall downstream results in an inverse effect, increasing the uplift force in the dam. The modeling demonstrated that increasing the horizontal distance between upstream and downstream cut-off walls also increases the uplift force. Placement of a second cut-off wall in the dam's heel can partially reduce erosion but is not beneficial for reducing uplift forces. The cut-off wall enhances the dam's resistance against overturning, consequently increasing the dam's safety factor to a value greater than one. Deepening the cut-off wall in the foundation improves resistance against overturning (Moharrami et al., 2015).

In this experimental investigation, two phenomena-uplift force and erosion-were examined through the modeling of a cut-off wall and drainage system. A key outcome of this laboratory study was that designing the cut-off wall in the middle of the dam structure will have a less impact on reducing uplift force (Alrowais et al., 2023). Placing the cutoff wall at the upstream heel was more effective in reducing uplift pressure compared to other placements during static conditions (Alrowais et al., 2023). It was observed that increasing the number and diameter of the installed drain pipes resulted in a considerable reduction in the uplift pressure head and exit gradient (Fadhil & Hassan, 2023). Increasing the penetration depth of the inner cut wall reduces the seepage flow so that it seeps in the flow rate. On the other hand, with the increase of the penetration depth of the internal cutting wall, the hydraulic depth and the relative drop of the total head increase (Haghdoost et al., 2023).

Diversion dams of river water diversion facilities are built to achieve the following goals:

- Raising the water level of the river changes the direction of the water flow towards the main channel.
- Regulation and control of water flow into the main channel.
- Preventing the entry of sediments into the main channel.
- Reduction of water level fluctuations in the river.

The purpose of this research is to investigate the effect of the thickness of the dam wall on the seepage and uplift forces of the case study of the diversion tower dam.

2. Material and Methods

2.1. Study area

A diversion dam is a dam that diverts all or part of the river from its natural course. The implementation of the project is in the diversion dam located 35 km northwest of Bojnord city and 5 km northeast of Ashkhane city. Objectives of Constructing the Borj Diversion Dam:

- Raising the river level for proper intake.
- Flood control.
- River stabilization.

2.2. Geometric Specifications of the Borj Diversion Dam

- The designed spillway of the Borj Diversion Dam is of the standard USBR Type III.
- The dam length along the flow path is 40 meters.
- The crest length is 48.4 meters.
- The height from the foundation is 14.8 meters.
- Water is conveyed through rectangular and trapezoidal channels with 5 km long corners.
- The volume of earthwork operations is 55,000 cubic meters.
- Concrete placement operations amount to 4,500 cubic meters.
- The body of the diversion dam consists of stone and mortar construction with a volume of 4,200 cubic meters.
- The Borj Diversion Dam has two cut-off walls, one upstream and one downstream.

The upstream cut-off wall is designed to control uplift forces, while the downstream cut-off wall aims to control seepage as well as prevent scouring at the end of the stilling basin and infiltration beneath the stilling basin. Figure 1 shows a view of the Borj diversion dam.

(a)

(b)

Figure 1. a) A view of the Borj diversion dam, b) A view of the water transfer lines of the Borj diversion dam.

In the Borj diversion dam, two cut-off walls has been installed. Based on prior research, the upstream cut-off wall appears to be effective in mitigating uplift forces. Conversely, the downstream cut-off wall plays a role in minimizing seepage and in preventing scour at the end of the stilling basin, as well as infiltration beneath the basin floor. The permeability of the cut-off wall is related to the natural characteristics of its materials, and in the numerical models carried out, the amount of seepage from the body of the cut-off wall has been considered zero.

2.3. Theory

If the horizontal and vertical stresses in the dam wall are more than the water pressure at the desired height, there will be no possibility of hydraulic failure. The thick cut-off must have the following conditions:

- These materials must be able to withstand deformation without cracking due to the pressure of the soil mass.
- The compressive strength should be low and to the extent that it does not prevent the deformation of the wall.
- Have good physical and chemical stability.
- Be resistant to erosion.
- Have a good performance.

Due to the selection of the alluvial environment beneath the diversion dam and the acceptance of Darcy's assumptions, as well as a uniform porous media, the flow has been considered to be laminar with very low velocities. Therefore, the momentum equations have been disregarded. Another point to note is that because the flow speed in the porous media is extremely low and the Reynolds number is much less than one, turbulent flow models have been avoided due to the laminar flow.

To derive the governing equations for subsurface water flow, the continuity equation should be combined with Darcy's Equation. The continuity equation is fundamentally based on the conservation of mass. If this principle is considered for a control volume in the following manner, we will have:

Change in Control Volume = Outflow Flux - Inflow Flux

The continuity equation is represented by the following formula:

$$\frac{\partial \mathcal{V}_X}{\partial x}+\frac{\partial v_y}{\partial \text{y}}+\frac{\partial v_Z}{\partial z}=-\frac{1}{\rho_W \forall}\frac{\partial M_W}{\partial t} \qquad (1)$$

In this Equation, v_x, v_y, and v_z are the flow velocities in the x, y, and z directions, respectively. In the Equation, *Pw*represents the specific mass of water, *V* denotes the control volume, *Mw* is the mass of the fluid within the control volume, and *t* stands for time. Darcy (1856) published his simple relationship for the flow velocity of water through saturated soil as follows:

$$V = ki \qquad (2)$$

Equation 2 is based on Darcy's empirical observations of water movement through clean soil mass.

Where:

- *V* is the flow velocity, representing the volume of water passing per unit time through a unit area perpendicular to the flow direction.
- *K* is the permeability coefficient.
- *i* is the hydraulic gradient.

The hydraulic gradient arises from the difference in hydraulic head between two points along the soil and is given by the formula:

$$I = \Delta h / \Delta l \qquad (3)$$

When the hydraulic gradient gradually increases, the flow transitions from a laminar state towards a turbulent flow. If the water flow in the soil remains laminar, the relationship between velocity and hydraulic gradient is directly proportional. However, in rocks, sand, and coarse aggregates, turbulent flow may occur.

If we incorporate Darcy's Equation into the continuity equation, Equation 4 is derived:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right) = S_S\frac{\partial h}{\partial t} \qquad (4)$$

Equation 5 relates to the flow of groundwater in a saturated media.

By applying boundary conditions for the execution of this project, Equation 5 can be rewritten as follows:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z}=\frac{S_S}{K}\frac{\partial h}{\partial t} \quad (5)$$

The operator ∇^2 is known as the Laplacian operator, which appears in two-dimensional flows in the form.

$$\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2} \quad (6)$$

In this study, the soil beneath the hydraulic structure of the Borj diversion dam is homogeneous and isotropic. Because the soil beneath the foundation of the Borj diversion dam has been saturated throughout its operational life, and the flow is steady, in addition to the homogeneity and isotropy of the underlying soil structure, equation 6 can be written in the following form Equation 7:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=0 \quad (7)$$

Or

$$\nabla^2 h=0 \quad (8)$$

n this context, equation 8 is a simplified version of equation 7 and is essentially the Laplace equation. If the hydraulic load does not change in the z-direction, the Equation simplifies as follows:

$$\frac{\partial h}{\partial z}=0$$

In this case, the flow transitions from a three-dimensional to a two-dimensional state.

In this study, the width (b) is considered constant (perpendicular to the plane), and horizontal flow is considered in the two-dimensional x-y plane.

$$T=bK \qquad S=S_S b$$

As a result of these assumptions, the Laplace equation can be written in the following form:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{S}{T}\frac{\partial h}{\partial t} \quad (9)$$

$$\nabla^2 h=\frac{S}{T}\frac{\partial h}{\partial t} \quad (10)$$

The level of water flow pressure in the soil's voids, which is the same as the pore pressure, is determined using the SEEP/W software. The total head and other required parameters are numerically calculated by solving Equation 10 in a geometric environment and specifying the boundary conditions for pore pressure.

2.4. Validation

In this research, numerical modeling was done using finite element method and using SEEP/W software to simulate the flow behind the tower diversion dam. But due to the conditions of diversion dam and the poor performance of Plaxis in the simulation of water flow in the soil, SEEP/W software was preferred. To ensure validation and reliability, the results were modeled and compared to validate the software employed in the current research (Mansuri et al., 2014).

The researchers employ the Seep/w model, which is based on the finite element method, to model the best location for the cut-off wall to minimize the uplift force. They do so by altering the angle and location of the cut-off wall.

The validation process consists of two parts:

- Model sensitivity with respect to the length of boundary conditions.
- Model sensitivity concerning meshing.

In the sensitivity analysis related to the length of the boundary conditions, the boundary length should be selected in such a way that the presence of a closed boundary at the ends of both models has no impact on the output results. This is because, in reality, there is no closed boundary at both ends of the diversion dam, and in computational modeling, it is not possible to model an infinite boundary. To further validate the findings, we compare one of the scenarios presented in another study by

Salmasi et al. using the modeling software. Salmasi et al. (2020) examined the effect of various positions of two cut-off walls beneath the hydraulic structure on reducing uplift force and exit hydraulic gradient.

3. Results and Discussion

Diversion dams are categorized according to their purpose and usage. Diversion dams are installed to raise the water level of a body of water to allow the water to be redirected. The redirected water can be used to supply irrigation systems, reservoirs, or hydroelectric power generation facilities. Figure 2 illustrates the schematic of the cut-off wall. Considering the figure, two important parameters in the numerical analyses are as follows:

- Upstream cut-off wall length *Lt*.
- Downstream cut-off wall length *Ld*.

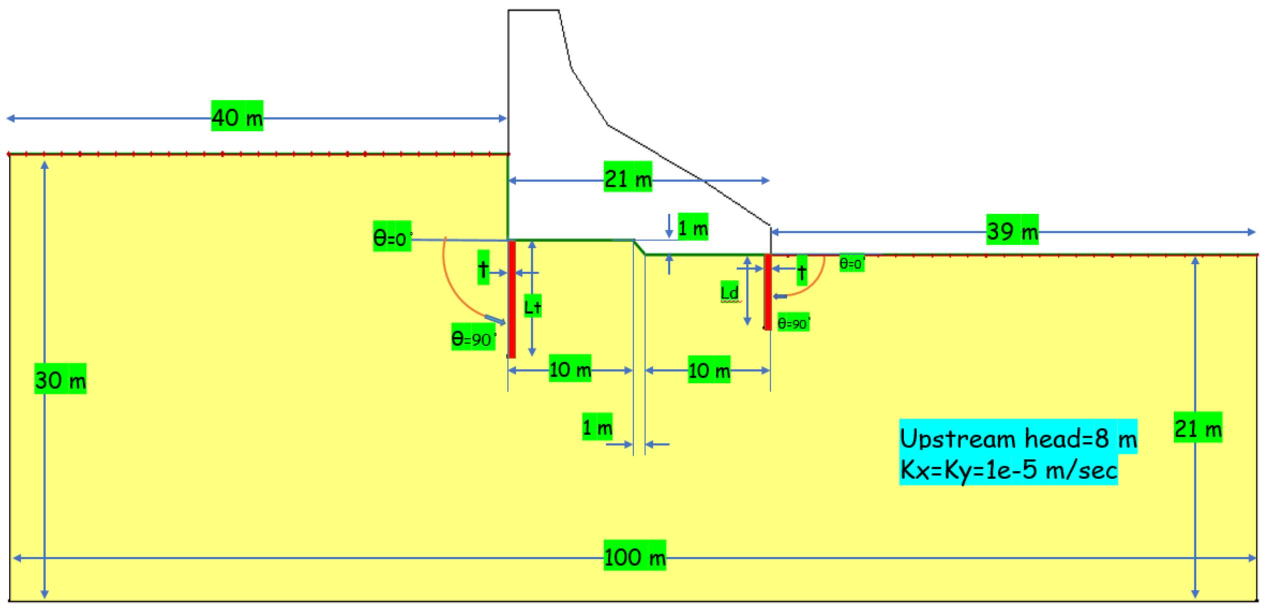


Figure 2. Schematic Cross-Section of the Cut-off Wall.

3.1. Investigating the Effect of Cut-off Length

The following scenarios have been examined to study the effect of the length of cut-offs:

- Upstream cut-off with a length of 6 meters and downstream cut-off with a length of 5 meters (Lt6 Ld5).
- Upstream cut-off with a length of 8 meters and downstream cut-off with a length of 3 meters (Lt8 Ld3).
- Upstream cut-off with a length of 8 meters and downstream cut-off with a length of 5 meters (Lt8 Ld5).
- Upstream cut-off with a length of 8 meters and downstream cut-off with a length of 7 meters (Lt8 Ld7).
- Upstream cut-off with a length of 10 meters and downstream cut-off with a length of 5 meters (Lt10 Ld5).
- Upstream cut-off with a length of 6 meters and downstream cut-off with a length of 3 meters (Lt6 Ld0).

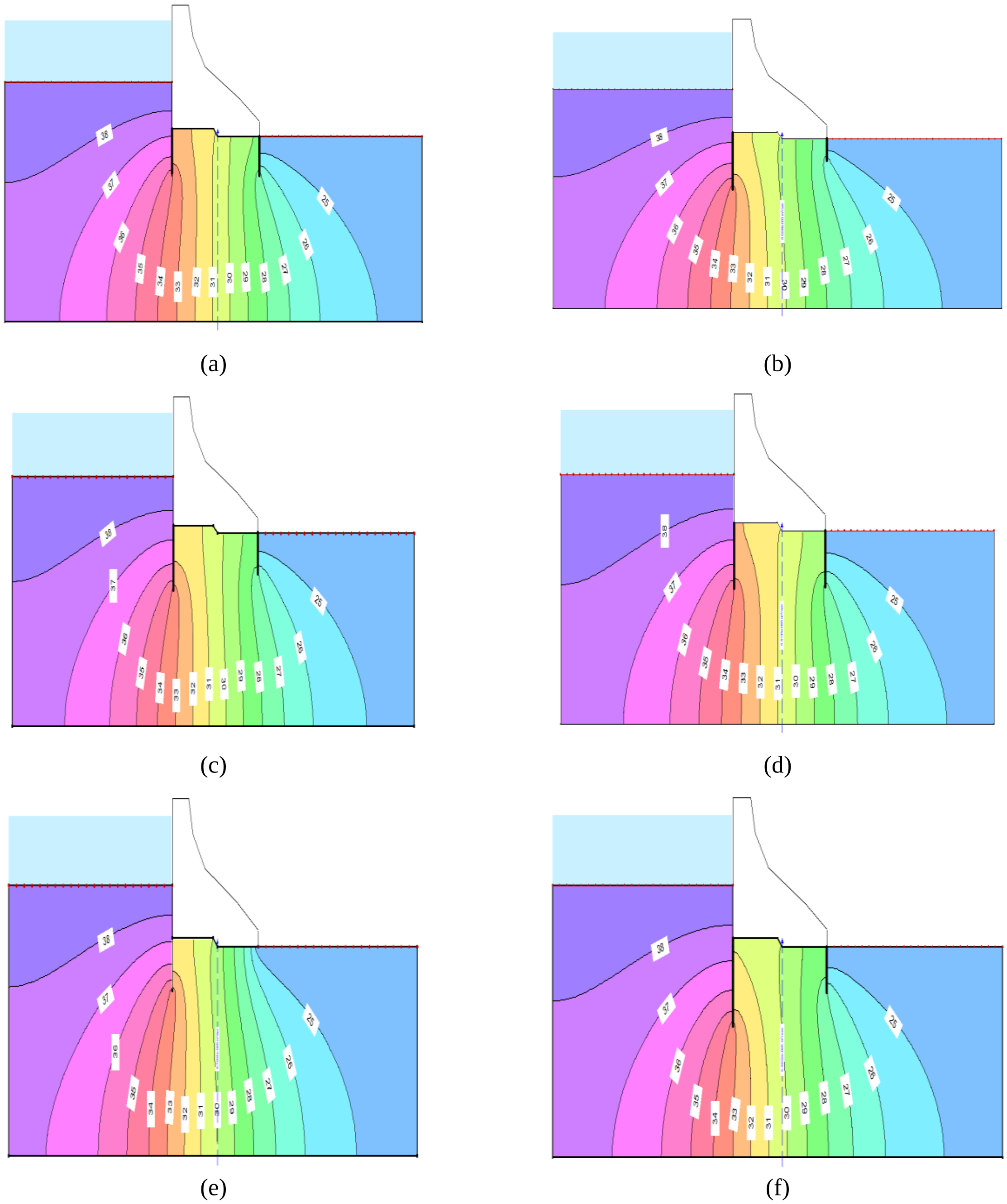


Figure 3. a) Contour lines for scenario Lt6 Ld5, b) Contour lines for scenario Lt8 Ld3, c) Contour lines for scenario Lt8 Ld5, d) Contour lines for scenario Lt8 Ld7, e) Contour lines for scenario Lt10 Ld5, f) Contour lines for scenario Lt6 Ld0.

In Figure 4, the graph sequentially shows the uplift force exerted on the dam cross-section, the equivalent uplift force, and the flow rate passing beneath the dam.

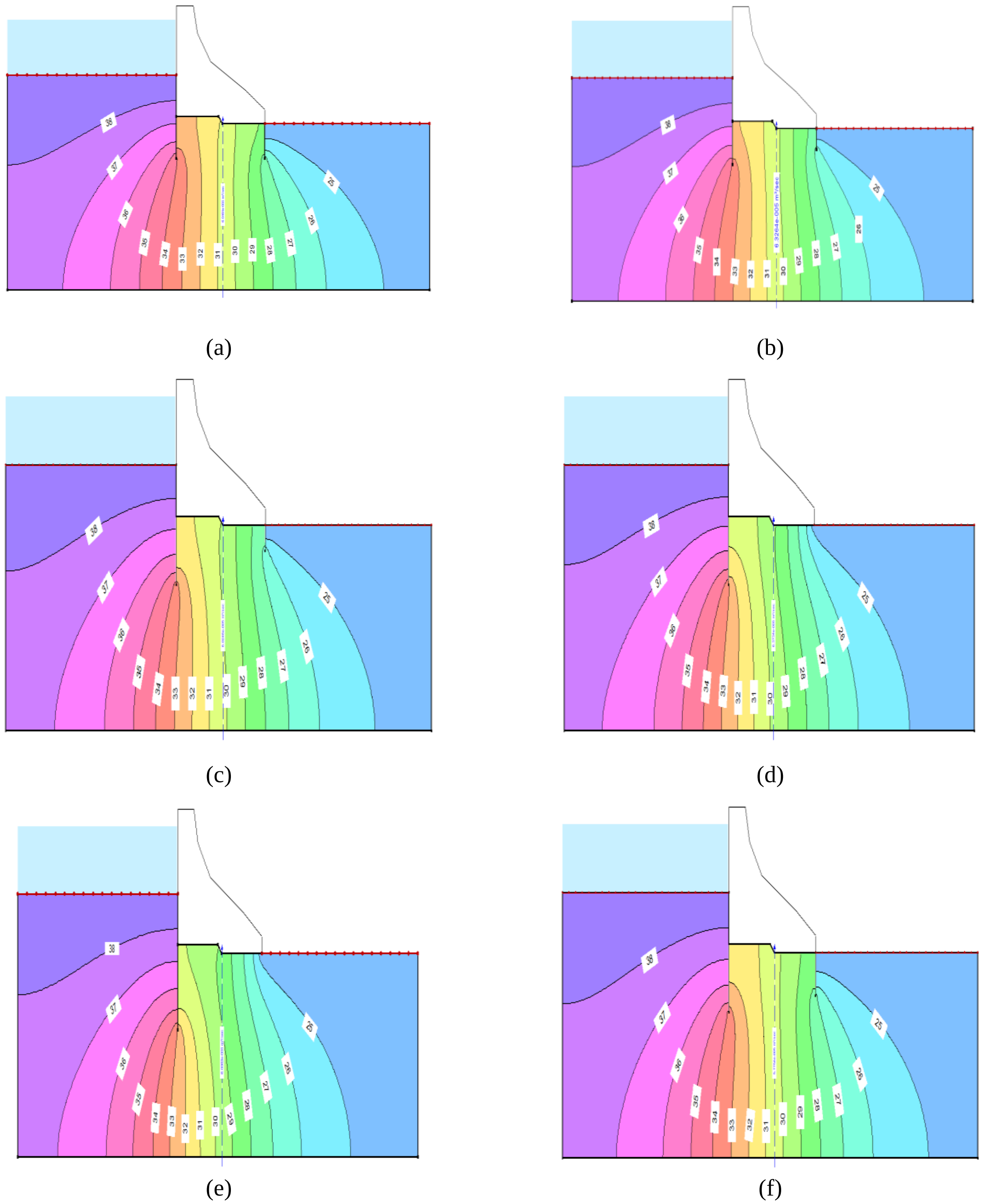
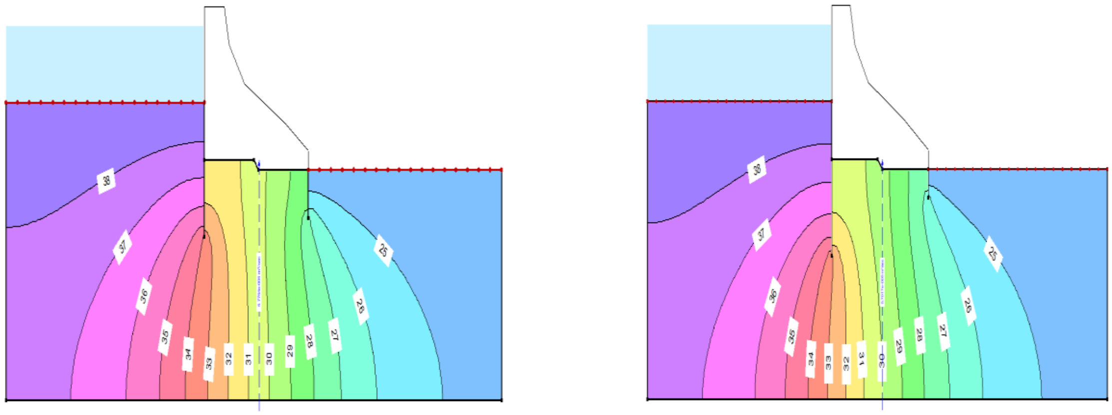


Figure 4. a) Contour lines for scenario Lt6 Ld3, b) Contour lines for scenario Lt6 Ld5, c) Contour lines for scenario Lt8 Ld0, d) Contour lines for scenario Lt8 Ld3, e) Contour lines for scenario Lt8 Ld5, f) Contour lines for scenario Lt10 Ld0, g) Contour lines for scenario Lt10 Ld3, h) Contour lines for scenario Lt10 Ld5.



(g) (h

Figure 4. (Continued)

The comparison of the effects of these length changes on the upstream and downstream cut-offs in the discharge rate for each of these changes is presented in Figure 5.

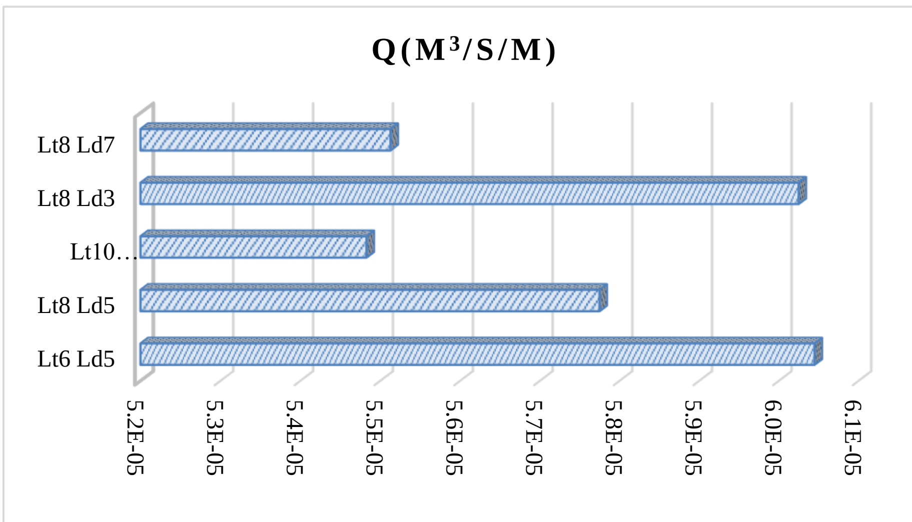


Figure 5. Bar chart illustrating the impact of changing the cut-off length on the flow rate in various scenarios.

Figure 6 depicts the effect of modifying the lengths of 6, 8, and 10 meters in the upstream cut-off compared to the lengths of 0, 3, and 5 meters in the downstream cut-off for achieving better outcomes in reducing the uplift force.

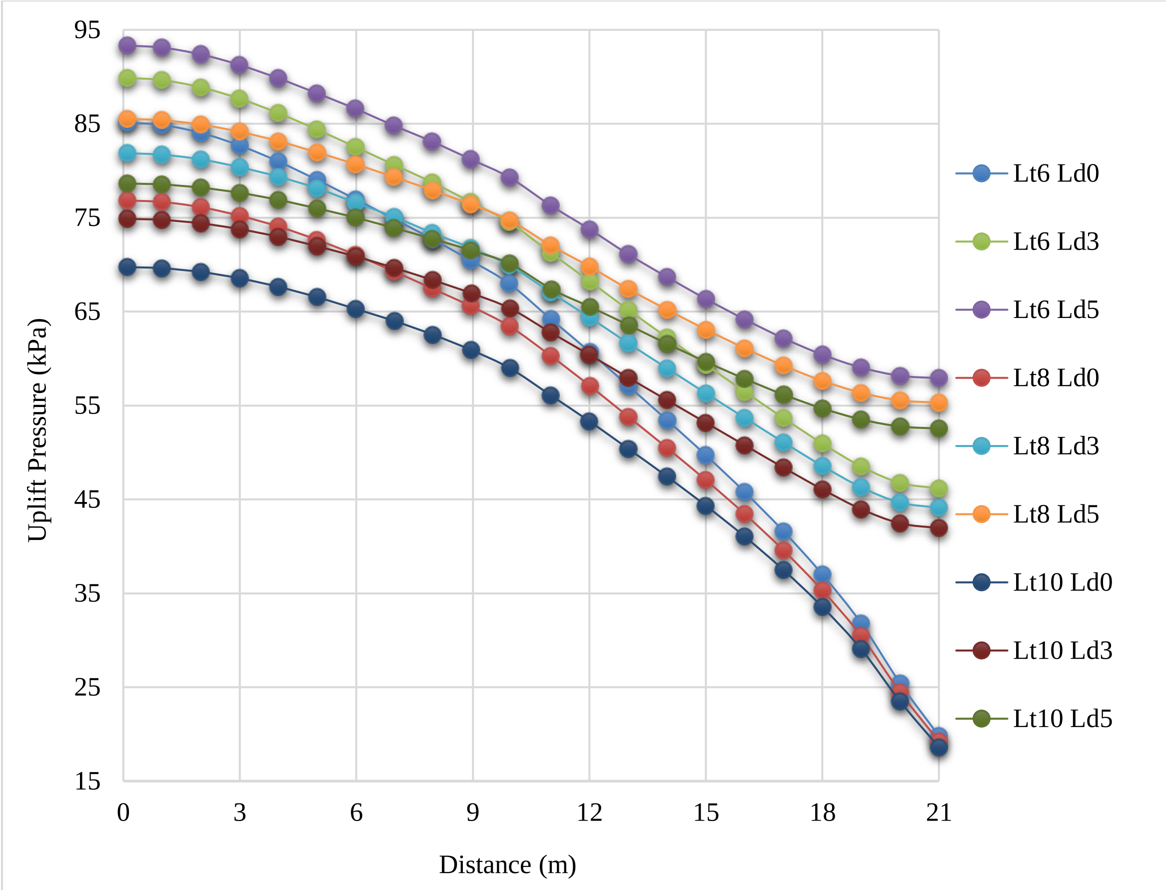


Figure 6. The effect of changing the length on the uplift force exerted on the cross-section of the dam.

The bar chart in Figure 7 demonstrates the influence of altering the length on the equivalent uplift force. This takes into consideration the lengths indicated in the preceding figure

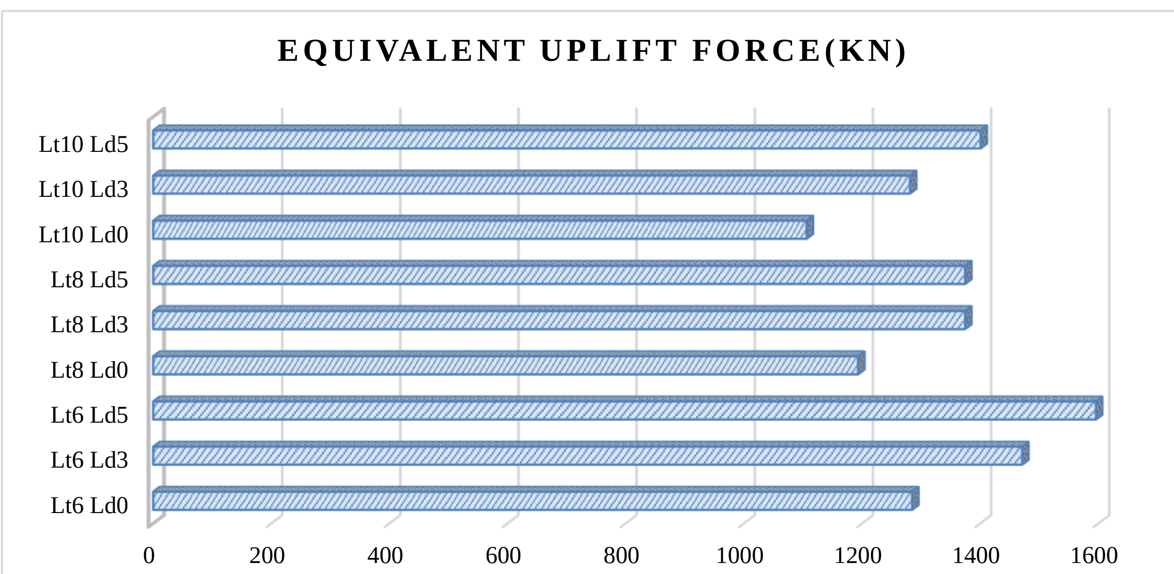


Figure 7. The effect of length variation on equivalent uplift force.

The bar chart in Figure 8 illustrates how different cut-off lengths, both upstream and downstream, impact the seepage flow rate at varying lengths.

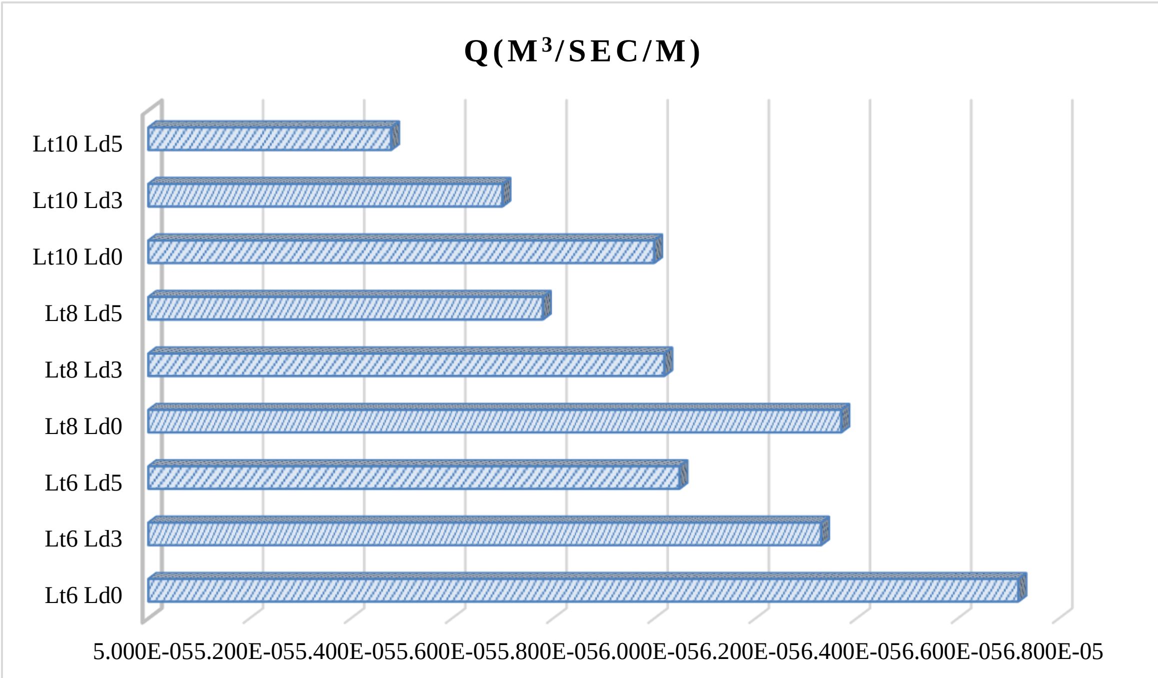


Figure 8. The effect of length changes on flow rate in various scenarios.

From the comparison of the obtained results, the following observations are made:

- Increasing the length of the cut-off wall, especially if located upstream, leads to a reduction in uplift force. However, increasing the height of the wall downstream will not be without effect.
- In dams that simultaneously use upstream and downstream cut-offs, contrary to past studies that often only used a single cut-off, it cannot be definitively stated that increasing the length of the upstream cut-off compared to the downstream one has a greater impact on reducing the uplift force, although the influence of the upstream wall is generally more noticeable.
- Extending the length of the cut-off wall results in reduced seepage flow. However, the effect of increasing the length of the upstream cut-off wall compared to the downstream one appears slightly more pronounced.

4. Conclusion

In this paper, the major contribution is to examine the influence of cut-off wall length on uplift forces in diversion dams, which is removed from the upstream and downstream dams, and the three important factors of the dams, i.e., the length of the dam, the thickness of the dam, and the angle, are implemented. The key findings of the research can be summarized as follows:

- The upstream cut-off wall has an effect on reducing uplift force; however, the downstream cut-off wall is primarily for sediment flushing and piping of the flow after the stilling basin. Furthermore, it is important that the scour basin, which arises due to hydraulic jump, should not be extended under the concrete stilling basin.

- Elevating the height of the cut-off wall leads to a reduction in both seepage and uplift force. However, optimizing the heights for both the upstream and downstream walls can further refine the system's performance.
- The research findings indicate that it is not accurate to assert that the downstream wall height has no significant impact. The downstream wall can play a meaningful role when coordinated with the upstream wall height.
- A cutoff wall at 0 degrees in the downstream and 75 degrees in the upstream is more suitable to reduce the uplift force. The 90 degree cutoff wall in the modeling increases the result of the uplift force. The proper inclination angle is between 60 and 75 degrees in order to reduce the angle of execution under the dam and reduce the uplift force of the angle.
- Thickness of cut-off do not have a noticeable change in reducing seepage flow rate and uplift force compared to thin ones

It should be noted that this research assumes that the cut-off is impermeable. It is recommended that future studies examine cut-offs with low permeability.

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Conflicts of Interest

The author declares no conflict of interest.

Availability of data and materials

The author declare that the data supporting the findings of this study are available within the paper. Source data are provided with this paper from

http://ecoursesonline.iasri.res.in/mod/page/view.php?id=2192

http://www.kalco.ir/?attachment_id=2269

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