The Effect of Cut-off Wall Angle on Seepage and Uplift Pressure under Dams

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Abstract

Seepage under dams can result in high uplift pressure experienced usually under the downstream of the dam which may lead to instability and potentially the failure of the dam. Cut-off walls are the primary solution to minimise the effects caused by the flow of water, as they extend the flow path which results in decreasing seepage, as well as uplift pressure and exit gradient. (Rice & Duncan, 2010)

This study aims to research how designing a cut-off wall at an angle under a concrete dam increases its efficiency. The angles will vary from 0° to 180°, progressively increasing at an interval of 30°. Following that, two walls will be designed originating from the same point at the nose of the dam, as well as another design where the walls are under both ends of the structure. The modal analysis will be completed using the finite element geotechnical software – PLAXIS 2D, as it has proved to be extremely precise in discharge analysis specifically (Galavi, 2010). A typical impervious concrete dam will be designed in the program in a uniform soil profile with the only variable being the angle of the cut-off wall and its originating point. This is done to put the attention simply on the discharge value that is obtained from the software. The feasibility of the construction will always be taken into account, as this study intends to complete research by taking a realistic and economic approach.

The results show that seepage is smallest when the cut-off wall is positioned at a 60° angle, as in this position water has to travel the furthest distance compared to the other configurations. In terms of uplift pressure, the dam experienced the least pressure when the wall is at 120°. As seepage and uplift pressure are the two main factors playing significant roles in the stability of dams – two combined configurations were introduced into the model in order to minimise both values; one being the addition of the 60° and 120° angle walls originating at both ends of the dam, and the other where the two formerly mentioned walls originated from the same point (the heel of the dam).

The configuration where the two walls are constructed under the heel and the toe show a significant decrease in seepage, as well as uplift pressure at the toe. When the two walls are both constructed originating from the same point (heel) – seepage is determined to be lower compared to when only one wall is considered, however a significant reduction in uplift pressure is not present.

When taking all data into account, the most feasible, economical and practical solution to decreasing seepage and uplift pressure considerably appears to be the arrangement where a 60° cut-off wall is constructed at the heel of the dam and 120 ° wall at the toe of the dam.

Key words: *Cut-off wall; Seepage; Uplift Pressure*

1. Introduction

Seepage is the flow of water from a high potential energy head to a low potential energy head. It is the phenomenon that brings upon the most complications when considering the stability of a dam. The flow underneath the dam can create uplift pressure and potentially erode the soil that supports the whole structure. The most efficient method to limit seepage is through the construction of a cut-off wall. The aim of this paper is to investigate the effect of designing a cut-off wall at an angle in the foundation of a concrete dam on seepage and uplift pressure experienced at the toe.

2. Problem description

The research process considers a typical 20-metre-high concrete dam, with design parameters which basically assume the dam to be impervious. This is done in order to put the attention strictly on the migration of water only through the soil strata. The dam is designed to simulate an almost full operating capacity by drawing the water level at 18 metres. This would allow for water to have a considerable effect on the stability of the foundation and some form of mitigating structure would be necessary. The most relevant material parameters used in the software are soil unit weight (kN/m^3), permeability (m/day), friction angle (°) and Young's Modulus (kN/m^2). Several cut-off wall configurations were considered where the angle varied from 0° to 180°. All angles are measured counter-clockwise, taking the top of the soil profile as a reference point.

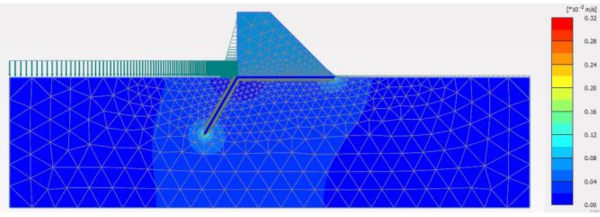

Figure 1: 60° Cut-off Wall Contour Discharge Graph

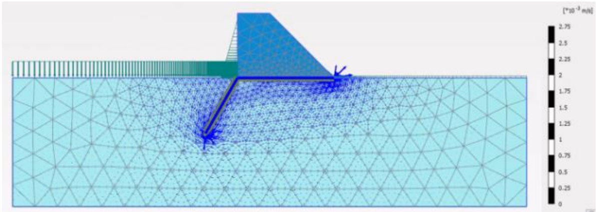

Figure 2: 60 Cut-off Wall Arrow Discharge Graph

PLAXIS 2D offers its users several ways to plot the groundwater flow graph. As seen in Figure 1 the water flow can be presented as a contour where the largest values for seepage are indicated in a colour alteration. Furthermore, Figure 2 presents the water movement of the model as arrows which change their size according to the value of discharge at that subdomain of the mesh.

3. Numerical results

Table 1 shows the discharge values obtained for each model directly under the cut-off wall and under the toe of the dam. As the primary objective here is to decrease the value of seepage moving under the dam the value obtained from under the wall is of larger relevance to the problem at hand. As seen from the data at 60 degrees - seepage is observed to be at a minimum value of $0.961*10^{-3} m^3/s/m$.

Table 1: Discharge Data for Angled Cut-off Walls

Inclination	***Discharge ($m^3/s/m$)***	
	Under cut-off wall	Under toe of dam
0°	$1.166*10^{-3}$	$1.164*10^{-3}$
30°	$1.022*10^{-3}$	$1.087*10^{-3}$
60°	$0.961*10^{-3}$	$1.045*10^{-3}$
90°	$1.043*10^{-3}$	$1.003*10^{-3}$
120°	$1.415*10^{-3}$	$1.098*10^{-3}$
150°	$1.375*10^{-3}$	$1.334*10^{-3}$
180°	$1.515*10^{-3}$	$1.509*10^{-3}$

The reason the 60° wall model experiences the least amount of seepage is due to the fact that with this arrangement the water path is extended the furthest, which basically means that the water molecules take a longer time to move from the point of higher potential energy to the point of lower potential energy. However, uplift pressure is closely related to seepage since the flow of water that passes through the soil profile is accompanied by an upward pressure acting on the horizontal base of the dam. The uplift pressure is maximum at the point just downstream of the hydraulic structure, when water is full up on the upstream side and there is no water on the downstream side (Mansuri & Salmasi, 2014).This can be clearly seen in Figure 2 where the arrows indicate that water begins to move upwards and apply pressure underneath the toe of the dam. This is where uplift pressure plays a major role in the stability of the dam. If the weight of the dam is insufficient in resisting this uplift pressure, this may lead to 'bursting' of the floor of the structure and ultimately collapse may occur. In PLAXIS this can be analysed by plotting the active pore water pressure graph. In this graph the varying levels of pressure are presented as contours.

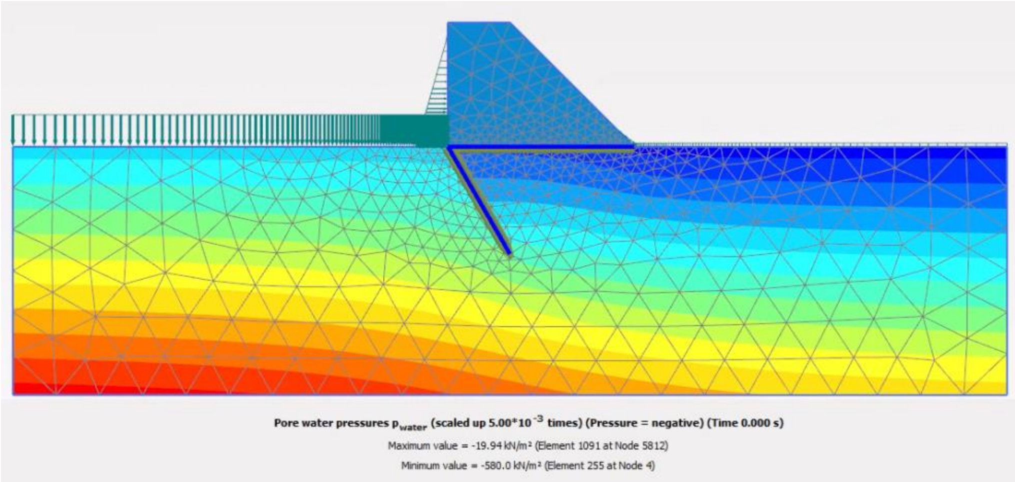

Figure 3: Pore water Pressure Distribution for 120° Angle

When plotting the pore water pressure graph in PLAXIS, the user can get quite a good understanding of where pressure is mostly focused on and what values to consider when designing the water retaining structure. From the results obtained from the created models and the data presented in Table 2, it is determined that the toe of the dam experienced the least amount of pressure of 20.73kN/m^2 when the cut-off wall is positioned at a 120° angle. The uplift pressure reduces the shear strength between the dam and its foundation and leads to tensile stress and consequently to the dam landslide and collapse (Irandoost, Reza Forghani, & Sayed Farizani, 2016). The difference in uplift pressures of the models is not that great due to the fact that the outcome or results are strictly related to how detailed and accurate the created models are and how closely they represent a realistic approach to a structure. It is assumed that with a more accurate and larger in scale model the difference in values obtained would be considerably more noticeable.

Table 2: Uplift Pressure for Angled Cut-off Walls

Inclination	Uplift Pressure (kN/m^2)
0°	20.89
30°	21.16
60°	21.12
90°	20.82
120°	20.73
150°	21.31
180°	21.06

The main goal of this research is to determine how to efficiently reduce both seepage and uplift pressure by finding the optimum orientation angle for a cut-off wall. With this in mind, two configurations where two walls are present in the foundation of the dam are investigated.

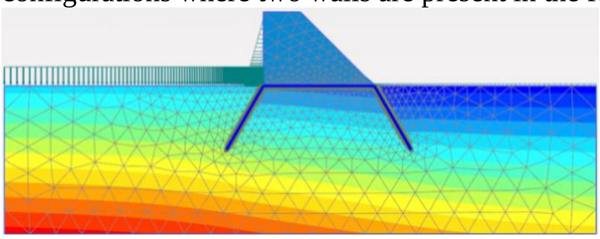

Figure 4: Combined Configuration Pore Pressure Graph

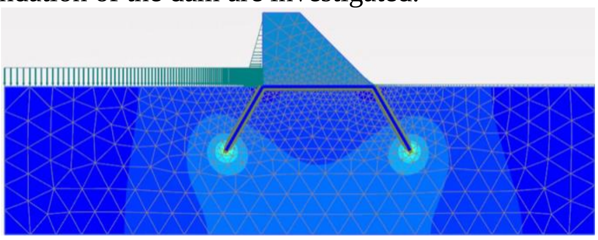

Figure 5: Combined Configuration Groundwater Flow Graph

Initial combined configuration consists of designing a 60° angle cut-off wall at the heel of the dam and a 120° angle wall at the toe of the dam. Seepage is discovered to have reduced considerably to about $0.742*10^{-3}m^3/s/m$ when compared to the base models, since water movement has been impaired quite well due to the addition of a second wall. Furthermore, uplift pressure experienced at the toe of the dam is calculated to be 20.00kN/m^2. Compared to the previously analysed models, a reduced value has definitely been achieved through the design of an additional obstruction of the water path. The pore water pressure experienced throughout the soil profile decreases progressively up to the toe of the dam until it is considered negligible enough for the design team to progress with further design solutions. Taking the reduction in seepage and uplift pressure of this combined model, it is only natural to attempt to even further reduce those values through the design of another combined configuration.

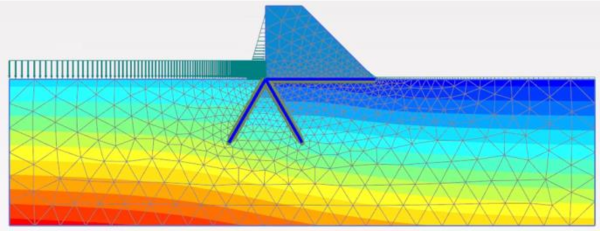

Figure 6: Second Combined Configuration Pore Pressure Graph

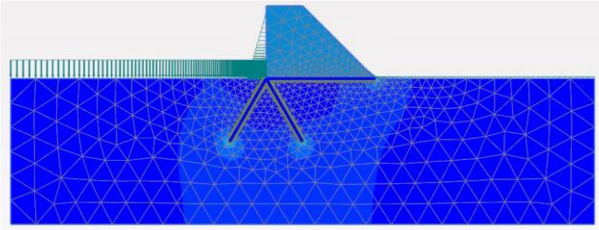

Figure 7: Second Combined Configuration Groundwater Flow Graph

The second combined model introduces the 60° and 120° angle cut-off walls originating from the same point under the dam – the heel. Seepage is determined to be 0.841*10^{-3}m^3/s/m, which is higher than the first combined model; however a reduction is still present when compared to the models that have only one cut-off wall designed in the foundation. This is again due to the fact that with the addition of a second wall the water path has been extended and it takes longer for water to travel in the subsoil. Uplift pressure at the toe of the dam is observed to be 20.55kN/m^2, which would still be considered a reduced value when compared to the initial models, however taking the first combined model into account the uplift pressure is slightly larger.

4. Conclusions

In this paper the effect of cut-off wall angle on seepage and uplift pressure under dams is investigated using the geotechnical software program – PLAXIS 2D. Several angled cut-off walls are considered, ranging from 0° to 180° and it is determined that at 60° - seepage is effectively reduced to its minimum value. Furthermore, uplift pressure is similarly reduced the most when the wall is positioned at a 120° angle. After considering several combined configurations of cut-off walls, it is determined that the most feasible, economical and practical solution to limiting both seepage and uplift pressure is the design of a 60° cut-off wall at the heel of the dam and a 120° wall at the toe of the dam as in this design both seepage and uplift pressure are at a minimum value.

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