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EFFECTIVENESS OF GROUTED CUT OFF WALL ON SEEPAGE CHARACTERISTICS OF AN EARTHEN DAM

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Abstract—**The analysis of hydraulic structures is critical as its failure can trigger the loss of lives and property. According to many historical studies, Seepage through and under the earthen dam is one of the most significant factors in the earth dam failures. To arrest the seepage, a cut off wall under the earth dam is one of the effective measures. In this research a numerical model is developed to study the effectiveness of cut off wall using FEM tool Plaxis-3D. Several numerical analyses were performed by changing the position of cut off wall along the dam's cross section for various water level conditions to determine the appropriate position. Further a parametric study is performed against different widths, depths and permeabilities of the cut off wall to check the effect of these parameters on the seepage characteristics. As a result, discharge, hydraulic gradient and pore water pressures in the earthen dam are monitored. The numerical results shows that the discharge and hydraulic gradient decreases, as the width and depth of the cut off wall increases, and permeability of the cut off wall decreases. It is also observed that the pore water pressures decrease at the downstream of the cut off wall.**

Keywords—**Earthen dam, cut off wall, FEM, discharge, hydraulic gradient, pore water pressure**

I. INTRODUCTION

The analysis of hydraulic structures is critical as its failure can trigger the loss of lives and property. According to many historical studies, seepage through and under the earthen dam is one of the most significant factors in the earth dam failures. Therefore, it is very important to investigate the effect of seepage on earthen dam. According to [1], 58.3 % of earth dam failures are caused by dam piping. [2], reported that, dam failure is caused by leakage and piping (35%), overtopping (25%), spillway erosion (14%), excessive deformation (11%), and sliding (10%). According to [3], seepage failures account for 35% of earth dam failures. [4], research also showed that about 35%, 30%, and 20% of earth dam failures are caused as a result of hydraulic, seepage, and structural issues respectively. Internal erosion and piping have been the main causes of failure in embankment dams, according to comprehensive studies by [5] and [6], because they destabilise the downstream slope. Several research have been described in the literature to study the impact of various factors on seepage control.[7], investigated seepage characteristics by employing the finite element method (FEM). They demonstrated the influence of mesh shape and size on the earth dam's seepage characteristics and noted that the mesh shape and size are minimal influence on seepage. They further reported that when the interior clay core is not used, the upstream slope and downstream slope angle has no effect on seepage.[8],stated that among the many options, increasing the length of the seepage path using sheet piles has proven to be beneficial in reducing seepage.[9], conducted a parametric analysis to investigate the impact of sheet pile length and position on several parameters such as pore water pressure, fluid flow vector, bending moment, and shear force.[10], performed two sets of parametric analysis, one with core and one without core. The study demonstrates a linear relationship between downstream flux quantity and maximum seepage velocity within the dam's cross section.[11]**,** established a finite element approach for seepage and stability analysis of an earthen dam in steady state and transient situations, with the behaviour of the soil being modelled using various constitutive relations such as linear elastic, nonlinear elastic, and plasticity laws. A finite-differences model for steady-state seepage was used by [12],to evaluate the total flow through for both the dam and its foundation, as well as the simplified flow only through the foundation. This study made several assumptions about the foundation's permeability ratios (horizontal to vertical) and cut off depths within the foundation[13],investigated the effectiveness of grout material on seepage characteristics of an earthen dam. They reported that when a grout curtain is employed on the upstream side, the flow velocity, exit gradient and pure water pressure are greatly reduced.

The earlier studies depict that seepage can be controlled by numerous ways, apart from these, use of cut-off wall may also play a vital role to reduce the seepage of an earthen dam. The objectives of the study are as follows:

- To evaluate the discharge and hydraulic gradient of an earthen dam under steady state condition for varying water levels in the reservoir.
- To study the effectiveness of cut-off wall in terms of its position, depth, permeability and thickness on amount of discharge and hydraulic gradient for various water level in the reservoir.
- To study the effect of cut-off on pore water pressure distribution, under steady state condition.

II.NUMERICAL MODELLING

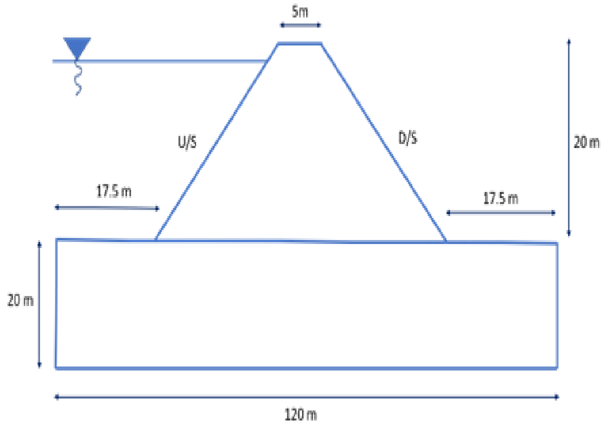

Fig.1. Cross- section of a homogenous earthen dam

Numerical analysis is carried by using FEM programme PLAXIS-3D. A steady state seepage analysis at six different water levels are performed with and without cut-off wall. For this the various factors that affect the efficiency of the cut-off wall are considered in terms of its depth, permeability, position and thickness. Fig. 1 depicts the schematic diagram of homogeneous earthen dam and its foundation used in the present study. The material properties of the soil and cut-off wall used in the model are given in Table 1 and Table 2. Medium mesh is considered throughout the study and a coarse ness factor of 1 is used for dam and 0.5 is used for cut-off wall.

Table 1: Material properties of soil used in the FE analysis [14]

Parameter	Units	Value	
		Dam body: Mohr - Coulomb	Foundation: Mohr-Coulomb
Drainage type	-	Drained	Drained
Soil unit weight above phreatic level(γ_{unsat})	(kN/m^3)	20.4	20.4
Soil unit weight below phreatic level(γ_{sat})	(kN/m^3)	21	21

Youngs modulus(E′)	(kN/m^2)	18.5 x 10^3	23 x10^3
Poison's ratio (v')	-	0.3	0.3
Cohesion (c')	(kN/m^2)	27	25
Friction angle (ϕ')	degree	22	28
Permeability (k)	(m/day)	0.2480	8.64

Table 2: Material properties of cut-off wall used in the FE analysis [15]

Parameter	**Units**	**Value**
Drainage type	-	Undrained (A)
Soil unit weight above phreatic level(γ_{unsat})	(kN/m^3)	18
Soil unit weight below phreatic level (γ_{sat})	(kN/m^3)	19
Youngs modulus (E)	(kN/m^2)	10 x 10^3
Poison's ratio (v)	-	0.35
Cohesion (c)	(kN/m^2)	10
Friction angle (ϕ)	degree	26
Permeability (k)	(m/day)	8.64 X 10^{-5}

III. EXPERIMENT AND RESULT

A. Seepage Analysis of the Dam and its Foundation Without Cut-off Wall

To obtain discharge and hydraulic gradient through dam and its foundation, here the case without cut-off wall is considered. Fig.2 depicts the geometry of the dam considered in FEM analysis. The results of discharge and hydraulic gradient for different water levels in the reservoir are summarised in Table 3.

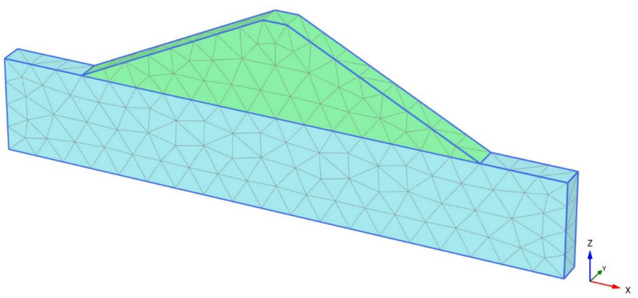

Fig.2. Geometry of the dam considered in FEM analysis

Table 3: Discharge and Hydraulic gradient of the dam and its foundation without cut-off wall

Water level (m)	**Discharge (m^3/day)**	**Hydraulic gradient**
18	**135.7**	**0.4196**
15	**111.8**	**0.3458**
12	**88.65**	**0.2741**
9	**65.91**	**0.2039**
6	**43.6**	**0.1348**
3	**21.66**	**0.06696**

From Table 3,it can be observed that increasing of hydraulic gradient and discharge amount are relatively proportional to the increasing water level in the reservoir. This increasing of discharge is too high and also it may be more in rainy or winter seasons. As a result, construction of cut-off wall can be one of the best options to be recommend in order to reduce the discharge rate.

B. Seepage Analysis of the Dam and its Foundation with Cut-off wall

Effect of Cut-off wall Depth

To investigate the effect of cut-off wall depth on seepage characteristics of the earthen dam, a cut-off wall with various depth of 5 m,10 m,15 m, and 20 m at the centre of the foundation is considered as shown in Fig.3.The analysis is performed at various water levels in the reservoir with cut-off wall permeability of 8.64 x10^{-5} m/day and 0.5 m thickness is considered.Fig.4illustratesthe variation of discharge and hydraulic gradient on cut-off wall depth for various water levels in the reservoir. It can be observed that when there is no cut-off wall, the amount of discharge and hydraulic gradient is relatively high and decreases significantly after construction of 20 m depth of cut-off wall. This is because the foundation material has a high permeability value, allowing a large amount of water to flow, whereas the cut-off wall permeability is very low.

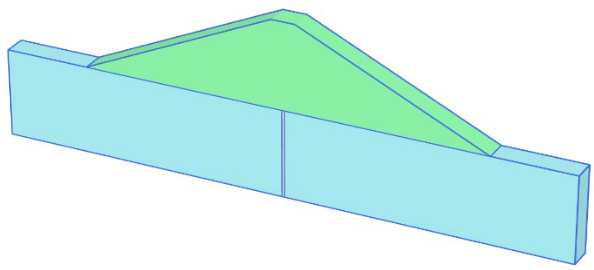

Fig.3. Geometry of the dam with Cut off wall at the centre of the foundation

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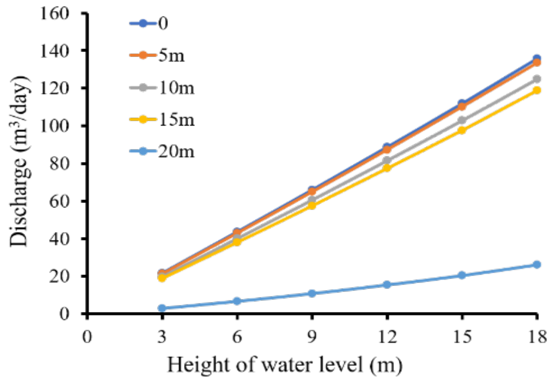

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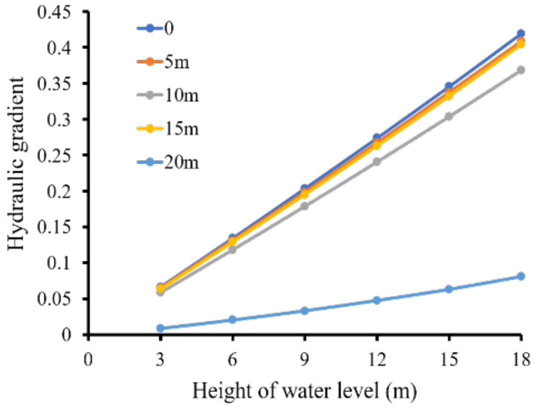
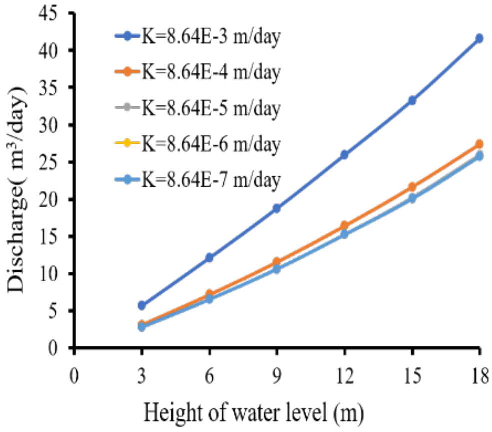


(b)

Fig.4. Effects of cut-off wall depth on a) discharge b) hydraulic gradient



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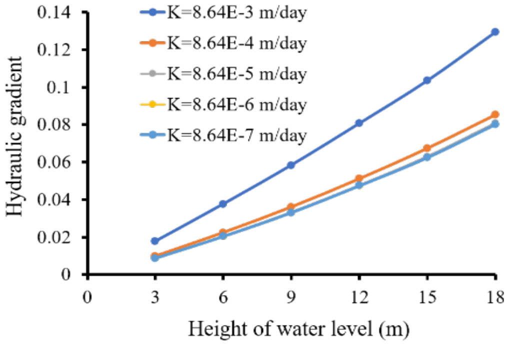

(b)

Fig.5. Effects of cut-off wall permeability on a) discharge b) hydraulic gradient

Effect of Cut-off wall Permeability

To investigate the effect of cut-off wall permeability on seepage characteristics of the earthen dam, a cut-off wall with various permeabilities of 8.64 x 10^{-3}, 8.64 x 10^{-4} ,8.64 x 10^{-5}, 8.64 x 10^{-6} and 8.64 x 10^{-7}m/day at the centre of the foundation is considered. The analysis is performed at various water levels in the reservoir with cut-off wall depth of 20 m and 0.5 m thickness of the cut-off wall is considered. Fig. 5illustratesthe variation of discharge and hydraulic gradient on cut-off wall permeability for various water levels in the reservoir. It has been observed that the amount of discharge and hydraulic gradient is relatively high when cut-off wall having permeability of 8.64 x 10^{-3} m/day and it decreases with decrease in permeability up to 8.64 x 10^{-5} and then remains constant even after decrease in permeability of the cut-off wall.

Effect of Cut-off wall Position

To investigate the effect of cut-off wall position on seepage characteristics of the earthen dam, a cut-off wall located at various positions from upstream to downstream with an interval of 20 m each, such as -40 m, -20 m, 0, 20 m and 40 m is considered. The analysis is performed at various water levels in the reservoir with cut-off wall permeability of 8.64 x 10^{-5} m/day and 0.5 m thickness of the cut-off wall is considered. Fig. 6 illustrates the variation of discharge and hydraulic gradient on cut-off wall position for various water levels in the reservoir. From this it has been observed that the amount of discharge is relatively high at downstream end when cut-off wall is provided at -40 m i.e., at upstream end and it is decreases when the cut-off wall position moves towards downstream end. The hydraulic gradient is relatively high at downstream end when cut-off wall is provided at -40 m and + 40 m i.e., at upstream end and downstream end and it is decreases when the cut-off wall provided at centre of foundation.

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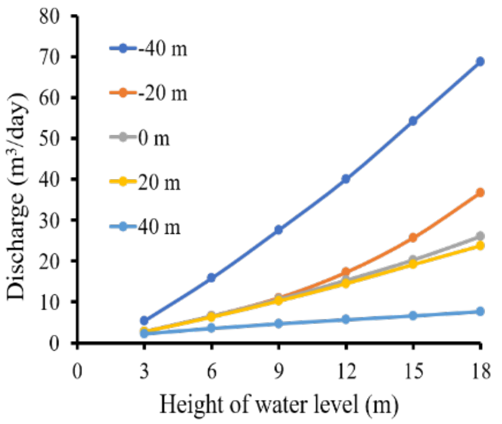

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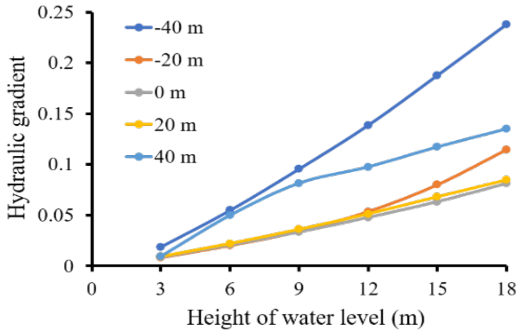
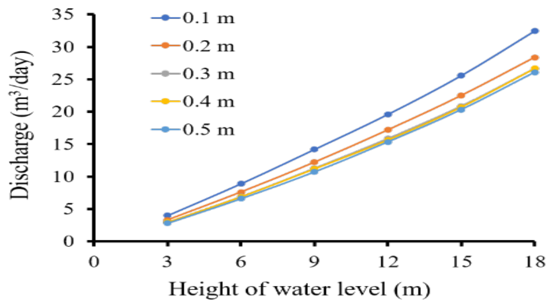


(b)

Fig.6. Effects of cut-off wall position on a) discharge b) hydraulic gradient

Effect of Cut-off wall Thickness

To investigate the effect of cut-off wall thickness on seepage characteristics of the earthen dam, a cut-off wall with various thickness of 0.1 m, 0.2 m, 0.3 m ,0.4 m and 0.5 m at the centre of the foundation is considered. The analysis is performed at various water levels in the reservoir with cut-off wall depth of 20 m and 8.64 x 10^{-5} m/day permeability of the cut-off wall is considered. Fig. 7illustratesthe variation of discharge and hydraulic gradient on cut-off wall thickness for various water levels in the reservoir. From Fig.7it has been observed that the amount of discharge and hydraulic gradient are relatively high when cut-off wall thickness is 0.1m and it decreases as the cut-off wall thickness increases. At higher thickness of cut-off wall (> 0.4 m), there is no significant effect of cut-off wall thickness on the measured values of discharge and hydraulic gradient.



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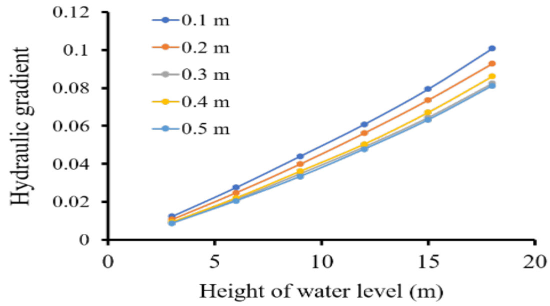

(b)

Fig.7. Effects of cut-off wall thickness on a) discharge b) hydraulic gradient

Effect of Cut-off wall on Pore Water Pressure

The effects of the cut-off wall on pore water pressure distribution are highlighted in this section. To investigate these effects, a cut-off wall of 20m depth having permeability 8.64x10-5 m/day and thickness is about 0.5m is considered at the centre of the foundation. Fig. 8 illustrates Pore water pressure distribution with and without effect of cut-off wall.

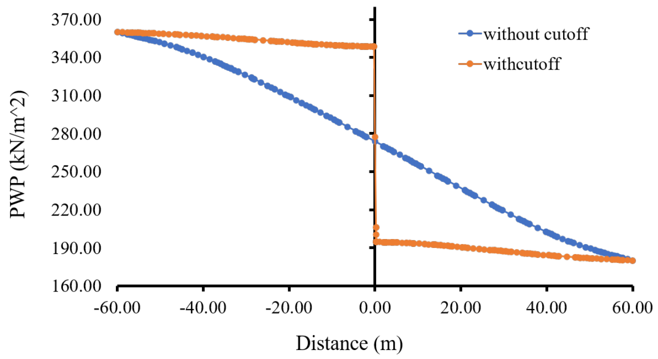

Fig.8. Distribution of pore water pressure with and without the effect of a cut-off wall

IV.CONCLUSIONS

- As water level in the reservoir increases, a proportional increase in hydraulic gradient and discharge amount are observed. The observed increase in discharge is too high due to higher permeability of the foundation material. As a result, construction of cut-off wall can be one of the suitable options to be recommend in order to reduce the discharge rate through the foundation of the earthen dam.

- The numerical simulation results shows that the amount of discharge and hydraulic gradient reduces significantly after construction of cut-off wall in the foundation of earthen dam.
- Parametric study conducted on the geometrical features of the cut-off wall revealed that with increase of cut-off wall depth the amount of discharge and hydraulic gradient through the earthen dam foundation decreases. It can be concluded placing the full depth of the cut-off wall in the dam foundation is the best option because it allows for the lowest values of discharge and provides the lowest hydraulic gradients.
- By varying the permeability of the cut-off wall, it is observed that as the permeability of the cut-off wall decreases the amount of discharge and hydraulic gradient also decreases. The discharge and hydraulic gradient remained constant after reaching the permeability of cut-off wall = 8.64×10^{-5} m/day.
- The observed discharge values are relatively high when cut-off wall is provided at upstream end and it decreases as the cut-off wall position moves towards downstream end and the optimum discharge is observed when the cut-off wall position is at downstream end. The hydraulic gradient is relatively high when cut-off wall is provided at upstream and downstream ends and the hydraulic gradient is minimum provided; the cut-off wall is at centre of the foundation.
- For the varied thickness of the cut-off wall, the amount of discharge and hydraulic gradient are relatively high when cut-off wall thickness is 0.1m and it decreases as the cut-off wall thickness increases. At higher thickness of cut-off wall (> 0.4 m), there is no significant effect of cut-off wall thickness on the measured values of discharge and hydraulic gradient is observed.
- The pore water pressure distribution is maximum on the upstream side of the earthen dam and decreases linearly towards the downstream side of the earthen dam without cut-off wall. It is observed that with installation of the cut-off wall the active pore water pressures increase at upstream side due to sudden abstraction of flow as a result the PWP are constant up to the cut-off wall and it decreases rapidly at location of the cut-off wall and then approximately it remains constant towards the downstream side.

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