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NUMERICAL ANALYSIS OF INFLUENCE OF CAVITIES ON SEEPAGE THROUGH EARTH DAMS

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Abstract. Seepage through earth dams is one of the main reasons of sudden earth dam failures through weakening the earth dam structure and the piping phenomenon. Cavities existence under the hydraulic structures can lead to heavy structural damages and financial losses as well as possibly humanitarian catastrophes. This research presents a numerical investigation into the effect of cavities existence on seepage through earth dams considering rapid drawdown conditions. The aim of present investigation is to simulate the effect of varying location of cavities in horizontal and vertical directions on seepage through earth dams. A series of 2D finite element models were developed using PLAXIS 2D software. A single cavity in various locations horizontally and vertically in subsoil of upstream and downstream slopes was considered in these simulations. The results of numerical simulations indicated that the cavities presence in subsoil of upstream face influences seepage through earth dam dramatically where the values of flow rate rises considerably. The numerical analysis outcomes also showed that varying location of cavities in horizontal direction is more influential than its location alterations in the vertical direction where the flow rate variations are considerably smaller under the effect of the cavities.

1 INTRODUCTION

A dam is a barrier that prevents or constraints water flow to generate a reservoir on its upstream face for several purposes, such as to supply water for irrigation, human consuming and industrial use, electricity generation, navigability and flood control. Dams may be constructed to achieve the one or more of the above purposes [1]. Depending on structure and material used for the body of dam, dams are categorized to embankment dams, gravity dams and barrage dam, with several subtypes. The two main types of embankment dams are earth-fill dams and rock-fill dams; embankment dams exemplify about 85% of all dams built [2]. Earth dam is likely the first type of dam was built and it is an economical hydraulical structure [3]. Earth dams have significant importance since they are considered one of the cheapest means for administering large volumes of water [4].

Dam failures are of serious issue where the failure of a moderate or large dam could cause a significant damage to property and infrastructure. A failure of earth dam may attribute to various reasons; dam failures can classify into three main categories: (1) Hydraulic: 40% (2)

Seepage: 30% (3) Structural failures: 30% [5]. Control of water seeping through or under earth retaining structures such as earth dams is one of the main challenges from their design and safety point of view; where the excessive seepage can bring about weakening in its structure and followed by an unanticipated failure owing to piping or sloughing [6].

Many procedures have been utilized to solve flow problems. Dupuit's, Schaffernak-VanIterson and Casagrande's solution were used to calculate the quantity of seepage and define phreatic surface through 2D homogeneous earth dams [7]. In recent decades, techniques in field of seepage analysis of earth dams have been witnessed significant progress as software analysis based on the numerical methods such as Finite Element and Finite Difference methods have emerged. [8] presented the application of numerical modelling to analyse seepage through earth embankments and dams using six computer software including MODFLOW, SEEP/W, ANSYS, PLAXIS, PDEase2D and SVFLUX. [9] used Finite Element modelling to simulate seepage analysis of the Walter Dam in USA, Geostudio software GEO – Slope (2004) and ANSYS software (2005) were utilized in this study. The comparison between Geostudio and ANSYS software results showed that a good harmonize between the results. [10] proposed a study to analyse stability and seepage of earth dam for steady state and transient condition using finite element PLAXIS 3D software. Based on the parametric (sensitivity) analysis Young's modulus E and angle of internal friction (φ) were used to identify the differences in stability of the earth dam.

Cavities existence in soils is a significant area of interest within the field of geotechnical engineering. Both natural and artificial cavities must be taken into account in the design and construction the structures, since cavities might cause considerable damage to structures and loss of lives [11]. Natural cavities could be created due to extinction of some seas or water areas, or as a result of the chemicals action or dissolution in soils or rocks including limestone, salt, dolomite and mainly gypsum because these materials could dissolve under the influence of water movement. As for artificial cavities can form due to the outputs of some factories being let under the ground or as a result of industrial mining operations or extraction of raw materials [12]. The water passing through soils or rocks carry with it some of the soft particles. The gradual removal of soil particles leads to development of cavities of various shapes and sizes. Moreover, movement of water through cracks and faults leads to expanded cracks and faults creating cavities which are often in irregular shapes and forms and are subject to collapse when amount to a critical size [13].

In the present study, the effect of the cavity existence on flow rate through the earth dam model has been investigated numerically under rapid drawdown condition utilizing computer software PLAXIS 2D, taking into account change of cavity location horizontally and vertically.

2 NUMERICAL MODELLING

2.1 PLAXIS 2D software

With fast evolution of computer science and digital computers, finite element method has become broadly dependent on software to help analyze complex problems in geotechnical engineering field. PLAXIS is one of the popular, powerful and specialist geotechnical engineering numerical simulations software based on the finite element method, specifically developed for the 2D and 3D analysis of deformation, stability and groundwater flow in geo-materials and geotechnical systems as well as soil-structure interaction modelling [14].

2.2 Geometry of the numerical model and cavity modelling

In this investigation, all analyses were accomplished using a numerical model developed in PLAXIS 2D code during rapid drawdown condition. Plane strain simulation using fifteen-node triangular elements was implemented to create the finite element mesh. In this investigation, the cavity is modelled as a tunnel without lining in PLAXIS 2D. The homogeneous earth dam model has a 15m crest height above the ground surface level, a crest width of 6m, subsoil depth of 20m and the inclination for both the upstream and downstream sides are 1Vertical: 2.5 Horizontal (1V:2.5H). At the beginning, the reservoir water level was assigned at level of 12m then it was quickly lowered to the level of 4m during 5 days to simulate rapid drawdown conditions. Figure 1 displays the geometry of numerical model and the finite element mesh.

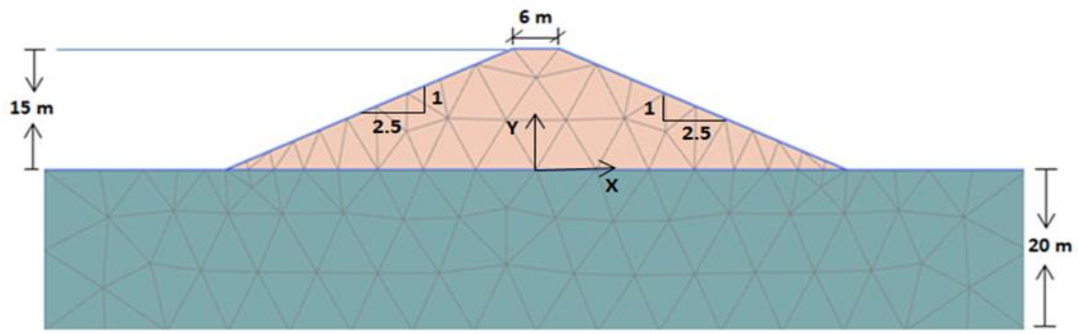

Figure 1: The earth dam geometry and finite element mesh

2.2 Materials parameters modelling

The elastic–plastic Mohr–Coulomb constitutive model was adopted for modelling the characteristics of the embankment materials and subsoil. In order to carry out the analyses, the input parameters included, unit weight of soil (γ), Poisson's ratio (v′), cohesion (C′), angle of dilatancy (ψ), internal angle of friction (ϕ′), coefficients of permeability in horizontal and vertical directions (k_x, & k_y respectively), and the Young's modulus (E′). Table 1 lists the input parameter values executed into the model.

Table 1: Model properties for embankment and subsoil

Parameters	Embankment	Subsoil	Unit
Model	Mohr-Coulomb	Mohr-Coulomb	
Drainage type	Drained	Drained	
γ unsaturated	16.0	17.0	kN/m^3
γ saturated	20.0	21.0	kN/m^3
v ′	0.33	0.3	
C′	25	5.0	kN/m^2
ψ, ϕ′	1.0, 22.5	5.0, 35.0	Degrees
kx, ky	10E-4	0.01	m/day
E′	2.0E4	5.0E4	kN/m^2

3 ANALYSIS AND RESULTS

The present study is an attempt to simulate and assess the effect of cavities existence in the subsoil of earth dam on flow rate through earth dam during rapid drawdown condition and cavity presence in the body is not considered. Parameters such as cavity depth and its horizontal location were also investigated. The seepage analysis was conducted employing the numerical model developed in computer software PLAXIS 2D for cases with and without cavities of varying locations. It is worth mentioning that all simulations were achieved considering the effect of existence of a single cavity of simplified circular cross-section shape with the diameter of 60cm.

3.1 Effect of presence and location of cavities

In this part of study, eight horizontal locations in the subsoil of upstream and downstream sides were selected to examine the effect of cavity location on flow rate through earth dam model. Cavity horizontal location (X) is the horizontal distance between cavity centerline and earth dam centerline. Coordinates of cavities locations in horizontal direction under upstream and downstream sides, as presented in Table 2. In all these analyses the cavities were situated at the depth of 1m below dam base surface although the horizontal locations change (L1 to L8; see Figure 2 for location details).

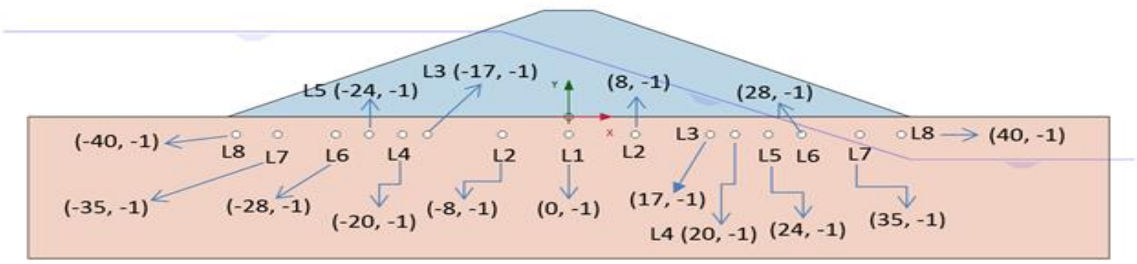

Figure 2: Location of cavities under upstream and downstream slopes

Table 2: Coordinates of locations of cavities in horizontal direction

Location of cavity	The coordinates of locations in X-axis (m)	
	Upstream	Downstream
L1	0	0
L2	-8	8
L3	-17	17
L4	-20	20
L5	-24	24
L6	-28	28
L7	-35	35
L8	-40	40

3.1.1 Cavities located under the upstream slope of the earth dam model

The influence of horizontal cavity location variation on flow rate are depicted in Figure 3. It is seen from the results that the cavities existence increases the flow rate significantly, where the values of flow rate increased from $2.7*10^{-3}$m/day for the model without cavities to $40.8*10^{-3}$m m/day for the model with cavity at location L2 (-8, -1). It is clear from results that the increasing of flow rate depends on location of cavities. The flow rate increased to $2.740*10^{-3}$m/day for model with cavity at location L8 compared to the case with no cavity, whilst this value was $54.05*10^{-3}$m/day for the case where the cavity was placed in location L2. The results trend show that the flow rate decreases with the increasing distance between the earth dam model centerline and the cavity centerline. Comparing the results for all locations considered, flow rate varies from $40.84*10^{-3}$ to $2.740*10^{-3}$m/day for as cavity location changes between L2 to L8. Figure 3 also shows a bug jump in the flow rate value as the cavity location moves from L1 (under the centerline) to the first location on the upstream side. This can be due to the faster downward stream under the upstream side as the gravity as well as the pressure head act affecting the flow rate.

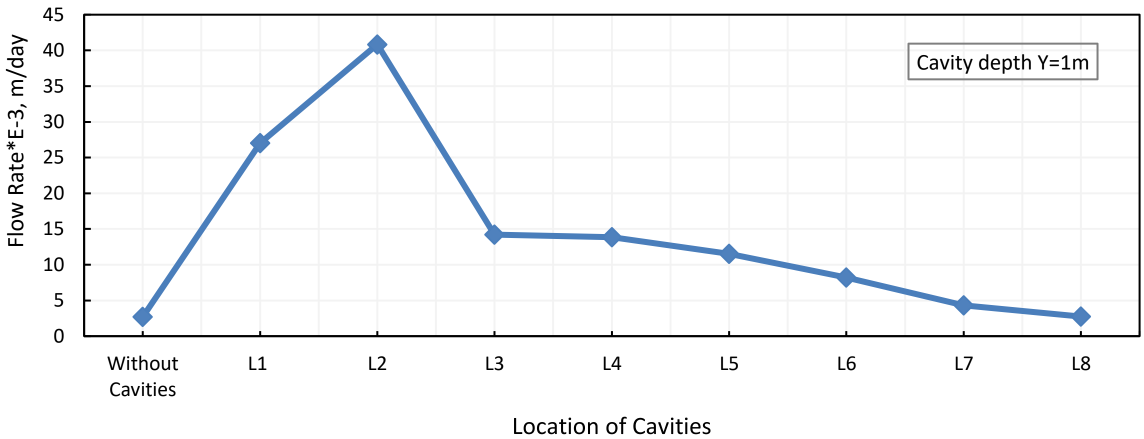

Figure 3: Flow rate vs. location of cavities under upstream slope – vertical position is kept constant at 1m below the dam base surface

3.1.2 Cavities located under the downstream slope of the earth dam model

Various locations of cavities under downstream slope varying horizontally were considered to study the effect of cavity location on flow rate. The results of analysis are presented in Figure 4. It is noted from results that the cavities existence increased the values flow rate for all locations of cavities from $2.7*10^{-3}$m/day for model without cavities to $27.03*10^{-3}$ m/day and $2.917*10^{-3}$m/day for models with cavities at locations L1 and L8 respectively. Furthermore, the simulation results pointed out that the values of flow rate decrease as the distance between earth dam centerline and cavity centerline increases. Values of flow rate decrease from $27.03*10^{-3}$m/day to $3.557*10^{-3}$m/day as the cavity relocates horizontally between locations L1 to L5. The values however show a slight increase with cavity location changing from L5 to L6, afterwards thought the previous fashion of changes continues as the cavity further relocates down the downstream side maintaining the general decreasing trend as the horizontal distance from the centerline increases.

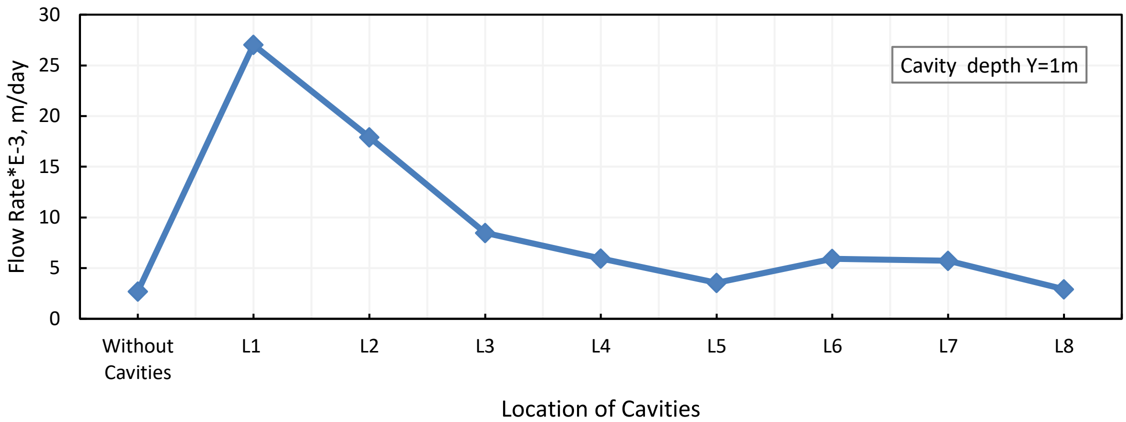

Figure 4: Flow rate vs. location of cavities under downstream slope– vertical position is kept constant at 1m below the dam base surface

3.2 Effect of cavity depth

The influence of variation in the cavity depth on flow rate through earth dam model has been studied in this part, four depths were considered for the cavity under upstream and downstream slopes; Y= 1, 2, 3 and 4m, where cavity depth (Y) is the vertical distance between embankment base and cavity centerline. The simulation was performed considering a single cavity of the diameter of 60cm. Cavity was being relocated horizontally through the same horizontal locations previously defined in Table 2 in various depths**.**

The results in Figure 5 show the effect of cavity depth for earth dam models with cavities located under upstream. It is clear that the flow rate values go up slightly with increasing cavity depth from Y=1m to Y=4m. This increase is more significant for the horizontal location L2 where the flow rate rises from $40.84*10^{-3}$m/day at the depth of 1m to $54.05*10^{-3}$m/day at the depth of 4m. It can be seen that the values of flow rate for horizontal locations L1, L4 and L5 reduce with increasing cavity depth from Y=1m to Y=2m; thereafter, the flow rate values follow the slight increase trend. For instance, location L1, where the flow rate reduces from $27.03*10^{-3}$m/day to $24.73*10^{-3}$ m/day when the depths of cavity changes from Y=1m to Y=2m, and then goes up to $26.27*10^{-3}$m/day at locations L1y1(horizontal location L1 and vertical location Y=1m), L1y2 and L1y3 respectively.

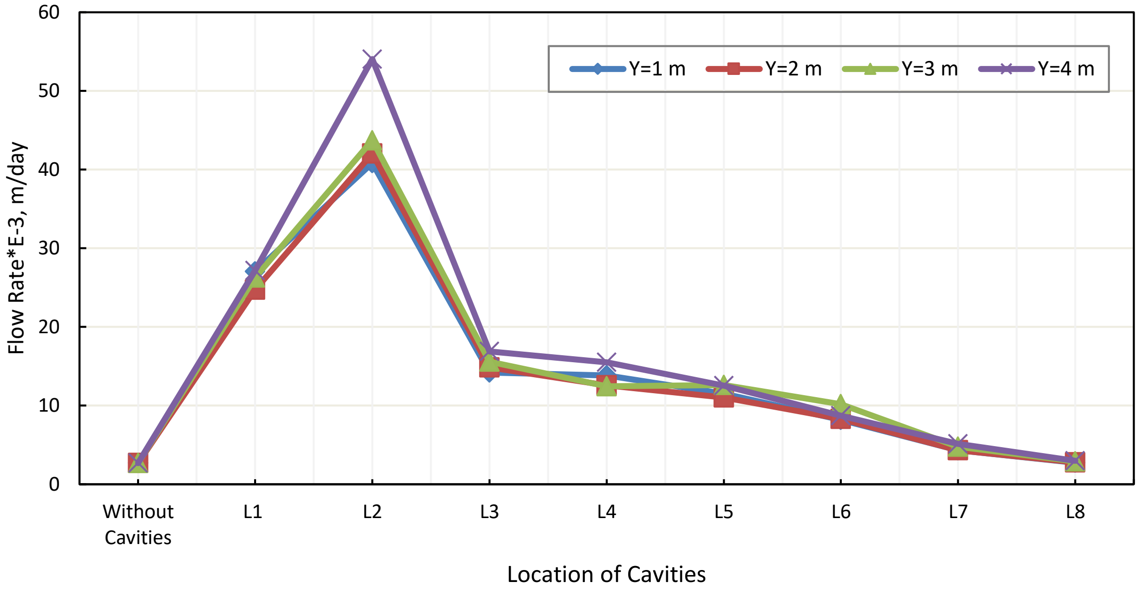

Figure 5: Flow rate vs. location of cavities under upstream slope for different depths

The effect of cavity depth on flow rate for earth dam models with cavities located under downstream are illustrated in Figure 6. The figure shows that he values of flow rate increases as the cavity depth increases from Y=1m to Y=4m for locations L1, L4, L5, L7 and L8. These flow rates changes are from $27.03*10^{-3}$ to $27.16*10^{-3}$m/day, $5.94*10^{-3}$ to $6.463*10^{-3}$ m/day, $3.557*10^{-3}$ to $3.687*10^{-3}$m/day, $5.726*10^{-3}$ to $18.255*10^{-3}$m/day and from $2.917*10^{-3}$ to $19.68*10^{-3}$m/day respectively. However, flow rate values show a slight decrease for models with cavities at horizontal locations L2, L3 and L6 as the depth changes from Y=1m to Y=4m ($17.93*10^{-3}$ to $16.31*10^{-3}$m/day, $8.482*10^{-3}$ to $7.59*10^{-3}$m/day and $5.913*10^{-3}$ to $4.983*10^{-3}$m/day respectively).

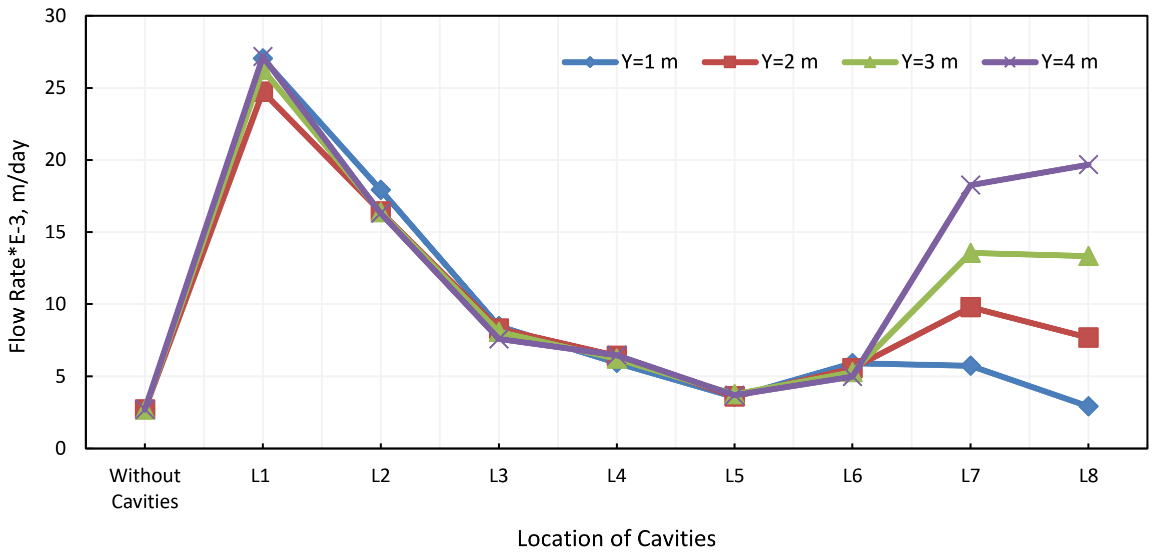

Figure 6: Flow rate vs. location of cavities under downstream slope for various depth values

3.3 Comparison between the effect of cavity existence under upstream and downstream slopes

Figure 7 shows a comparison between the influence of the cavities existence beneath upstream and downstream slopes. The comparison highlights that, in general, presence of cavities under the upstream side of earth dam is more influential on flow rates than their presence under the downstream of the model earth dam in rapid drawdown conditions. The flow rates increase from $2.7*10^{-3}$m/day to $54.05*10^{-3}$m/day from models without cavities to the ones with cavities under the upstream side, whereas this increase when the cavities are placed under the downstream side is from $2.7*10^{-3}$m/day to only $27.16*10^{-3}$m/day, about half the value obtainable for the cavity presence under the upstream side.

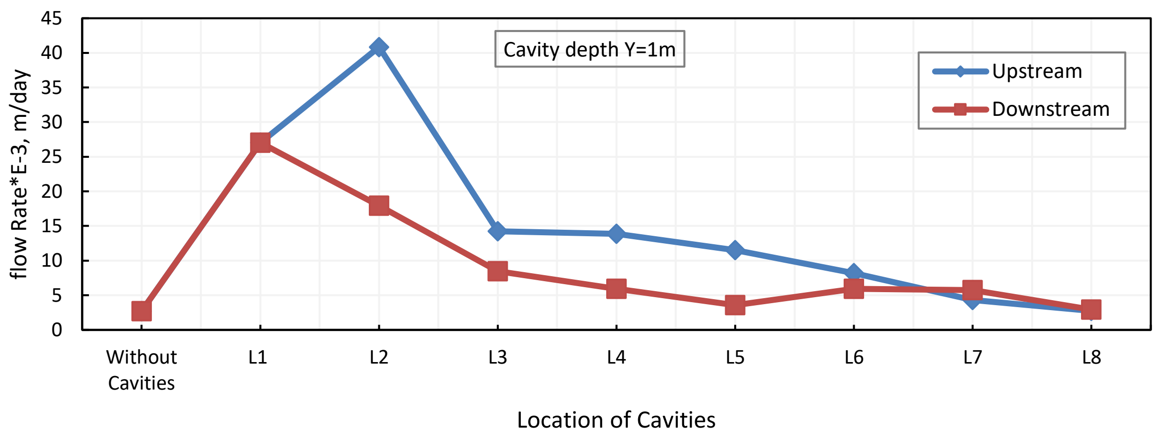

Figure 7: Effect of presence of cavities under upstream and downstream on flow rate

4 CONCLUSIONS

The present investigation is an attempt to examine the impact of cavities existence in varying horizontal and vertical locations on flow rate through earth dam model. Based on the presented analyses accomplished the following conclusions could be drawn:

- Presence of cavities under the base of earth dam dramatically increases the flow rates through the base considering rapid drawdown conditions.
- Cavities existence beneath the base under the upstream side of the earth dam places a greater impact on flow rate through earth dam compared to the cases where the cavities are situated in subsoil of downstream side.
- Variation of cavity location in the horizontal direction influences the flow rates greatly whereas this influence is smaller as the cavity relocates vertically
- Studying the effect of variations in cavity locations reveals that existence of cavity and its effect on changes in flow rates compared to the case with no cavities becomes less important as the distance between the cavity centerline and the earth dam model centerline increases horizontally.
- Increasing distances between the cavity centerline and the earth dam model base surface have smaller effect on the changes in flow rate; however, in general, as the depth of cavity increases the flow rate through the earth dam also increases.

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