



OPTIMAL LOCATION OF DRAINAGE GALLERY UNDER GRAVITY DAM BY USING FINITE ELEMENT METHOD

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Abstract:

Gravity Dams depend mainly on its own mass to resist the effecting uplift pressure. The effect of uplift pressure can be reduced by using a drainage gallery. The optimum position of the drainage gallery under gravity dam results maximum drain reduction factor. In this study, numerical method (two dimensional finite element) are used to analyze hydraulics of uplift pressure under the gravity dam and its effect on usage of gallery drain, and without gallery drain for different reservoir and drain location along the base of the dam. Two models used once without sheet pile and another with sheet pile. Drain reduction factor (DRF) had been calculated to demonstrate the effect of used gallery drain in the system. The results indicate that the gallery drain nearest the upstream side close to $X_d/B=0.167$ results in maximum (DRF) close to 0.494, and can be achieved as the optimum position of the drainage gallery, at which seepage discharge entering the drainage gallery is maximum. The results of comparison between the two models showed that the usage of gallery drain and sheet pile in the system reduces the uplift force more than 40% and 20% respectively. The analysis process depends on computer program package "SLIDE V.5.005".

Key Words: Uplift Pressure, Seepage, Gravity Dam, Drainage Gallery & SLIDE Program

1. Introduction:

Hydraulic structures like dams, regulators, weirs, aqueducts, boxes culvert, gates, retaining walls...etc are either founded on a nonporous rock soil or a porous soil. The presence of a difference in water level between upstream and downstream across the hydraulic structure results in water seepage or filtrations through the porous soil under the hydraulic structure. The analysis of seepage through soil requires calculation of uplift pressure under the hydraulic structures [1]. As civilizations developed, dams were constructed for a specific purpose such as retains water to create an impounding reservoir and passes the water over or through it when required or when the water is surplus [2]. Applying optimization techniques for determine the optimal location of drainage gallery under gravity Dam is not a new idea. Various techniques have been applied in an attempt to find better location corresponding optimum position of the drainage gallery under gravity dam results maximum drain reduction factor. The [3] proposed generally based predictable certain design criteria for the upward pressures caused by seepage under the foundations of gravity dams. [4] Explained that 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. [5] Determined that, at drainage gallery, the best uplift pressure is equal to the hydrostatic pressure at toe of dam base plus the third difference of the hydrostatic pressure at heel and toe of the dam base. [6] Showed that uplift can be modeled in several ways in a finite element analysis of concrete dams. Also uplift pressures within the rock and concrete and relative foundation stiffness have an effect on the fracture mechanics analysis of the dam foundation interface. [7] Used case of lining subjected to high uplift

pressure in a sand model, based on minimum uplift pressure acting on the lining, optimum numbers and locations of relief valves was investigated. [8] Determine experimentally the optimum location of the drainage gallery underneath gravity dam. [9] Investigated the influence on the upward pressures of the number and location of the drainage galleries, of the dimensions, coarseness and inclination of drains for a dam on homogeneous and isotropic material. [10] Showed that if the uplift pressure is not counterbalanced by the weight of the floor, the structure may fail by rupture of a part of the floor.

Abbreviations and Acronyms:

U: velocity component in x-direction. (L/T)

V: velocity components in y-direction. (L/T)

k_x, k_y : Hydraulic conductivity in x, y directions respectively. (L/T)

H: Piezometric head (L)

k_x : Hydraulic conductivity in the horizontal direction.

k_y : Hydraulic conductivity in the vertical direction.

U: velocity component in x-direction.

V: velocity component in y-direction.

Ψ : Stream function.

I. Finite Element Method

The finite element formulation for steady-state fluid flow in two dimensions is as follows:

$$\int_A \begin{bmatrix} \frac{\partial}{\partial x} \{L\} \\ \frac{\partial}{\partial y} \{L\} \end{bmatrix}^T \begin{bmatrix} k_{wx} & 0 \\ 0 & k_{wy} \end{bmatrix} \begin{bmatrix} \frac{\partial}{\partial x} \{L\} \\ \frac{\partial}{\partial y} \{L\} \end{bmatrix} dA \{h_{wn}\} \int_S \{L\}^T \bar{v}_w dS = 0 \quad \dots(1)$$

Where $\{L\}$ = matrix of the element area coordinates $\{L_1 \ L_2 \ L_3\}$

L_1, L_2, L_3 : area coordinates of points in the element that are related to the Cartesian coordinates of nodal points in the following equations:

$$L_1 = (1/2A)\{(x_2y_3 - x_3y_2) + (y_2 - y_3)x + (x_3 - x_2)y\}$$

$$L_2 = (1/2A)\{(x_3y_1 - x_1y_3) + (y_3 - y_1)x + (x_1 - x_3)y\}$$

$$L_3 = (1/2A)\{(x_1y_2 - x_2y_1) + (y_1 - y_2)x + (x_2 - x_1)y\}$$

x_i, y_i ($i=1,2,3$) Cartesian coordinates of the three nodal points of an element x, y Cartesian coordinates of a point within the element.

A = area of the element

$$\begin{bmatrix} k_{wx} & 0 \\ 0 & k_{wy} \end{bmatrix} = \text{matrix of the water coefficients of permeability.}$$

$\{h_{wn}\}$ = matrix of hydraulic heads at the nodal points, which has the form:

$$\begin{Bmatrix} h_{w1} \\ h_{w2} \\ h_{w3} \end{Bmatrix}$$

$\bar{v}_w$ = External water flow rate in a direction perpendicular to the boundary of the element

S = perimeter of the element

Equation (1) can be rearranged and simplified to produce this governing flow equation:

$$\int_A [B]^T [k_w] [B] dA \{h_{wn}\} - \int_S [L]^T \bar{v}_w dS = 0 \quad \dots(1a)$$

Where $[B]$ = the matrix of the derivatives of the area coordinates, it can be written as:

$$\frac{1}{2A} \begin{Bmatrix} (y_2 - y_3) & (y_3 - y_1) & (y_1 - y_2) \\ (x_3 - x_2) & (x_1 - x_3) & (x_2 - x_1) \end{Bmatrix}$$

In order to solve for the hydraulic head at each node, either the hydraulic head or flow rate must be defined for each node. Then, equation (1a) can be written for each element to form a set of global flow equations, which may then be solved using an iterative method. Once the hydraulic head at each node has been calculated, other quantities such as hydraulic head gradients or element flow rates can be calculated. The hydraulic head gradients in the x and y directions can be calculated for an element by taking the derivative of the element hydraulic heads with respect to x and y:

$$\begin{Bmatrix} i_x \\ i_y \end{Bmatrix} = [B]\{h_{wn}\}$$

Where i_x, i_y hydraulic head gradient within an element in the x and y directions.

Finally, the element flow rates can be calculated using Darcy's law, the hydraulic head gradients and the coefficient of permeability as follows:

$$\begin{Bmatrix} v_{wx} \\ v_{wy} \end{Bmatrix} = [k_w][B]\{h_{wn}\}$$

Where v_{wx}, v_{wy} = water flow rates within an element in the x and y directions.

The hydraulic head gradients and flow rates at each node are calculated by determining a weighted average (based on element area) of the quantities in the elements surrounding the node.

2. The Uplift Pressure:

It is one of the most important factors that are related to the safety and stability of hydraulic structures. It refers to the pressure of the water seepage under the structure that pushes the floor upward and tends to wash away the soil under it leading to piping phenomenon. 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. [Karim, A. Rizgar, 1987 – 1988]. If the uplift pressure is not counterbalanced by the weight of the floor, the structure may fail by rupture of a part of the floor. [Al-Delewy et.al, 2006]. The problems of piping and uplift are practically tackled through a variety of methods of seepage control, aiming at ensuring the safety of the respective structure and at the same time saving the possibly-seeping water. The common provisions in this respect are (Upstream blanket, Upstream or/and downstream cut-offs, Subsurface drain on the downstream side, Filter trench on the downstream side, Grout curtain, Gallery drain, Mixture of two ways or more, Weep holes and Pressure relief wells on the downstream side. [Al-Delewy et.al, 2006].

3. Governing Equations:

(a) The General Equation of Steady Seepage Flow:

The two-dimensional anisotropic components of seepage through porous media according to the general Darcy's Law form are [Freeze and cherry, (1979)].

$$U = k_x I_x = -k_x \frac{\partial H}{\partial x} \quad \dots (2a)$$

$$V = k_y I_y = -k_y \frac{\partial H}{\partial y} \quad \dots (2b)$$

The continuity equation for two-dimensional and incompressible, irrotational flow is:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \quad \dots (3)$$

Substituting Darcy's (2) in equation (3) results in:

$$\frac{\partial}{\partial x} (k_x \frac{\partial H}{\partial x}) + \frac{\partial}{\partial y} (k_y \frac{\partial H}{\partial y}) = 0 \quad \dots (4)$$

For homogenous and isotropic soil, the hydraulic conductivity is equal everywhere in all directions: $k_x = k_y$

Then equation (4) would be:

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} = 0 \quad \dots (5a)$$

Equation (5a) is called Laplace Equation and it is similar to Laplace Equation of velocity potential for ideal fluid flow or non-viscous, irrotational flow. Laplace equation represents the condition of steady-state laminar flow and different methods to find the piezometric head of the flow domain can be used. For homogenous and anisotropic soil the hydraulic conductivity is equal everywhere and not equal in all directions, i.e.: $k_x \neq k_y$. Then Laplace equation becomes:

$$k_x \frac{\partial^2 H}{\partial x^2} + k_y \frac{\partial^2 H}{\partial y^2} = 0 \quad \dots (5b)$$

There is another benefit function for the flow through porous media, which is called stream function $\Psi_{(x,y)}$.

$$U = \frac{\partial \Psi}{\partial y}, V = -\frac{\partial \Psi}{\partial x} \quad \dots (6)$$

From the similarity between the flow through porous media and the ideal flow, where the flow is irrotational and the vorticity equal to zero, the expression for this relation is:

$$\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} = 0 \quad \dots (7)$$

Substituting equation (6) into equation (7) results in:

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} = 0 \quad \dots (8)$$

This represents Laplace equation for stream function.

(b) Seepage Equation for Homogeneous Isotropic Foundation:

The seepage underneath hydraulic structure (gravity dams) may be represented by:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \quad \dots (9)$$

The subsurface flow under hydraulic structures will mainly be two dimensional, as the width of a river is so considerable that the subsurface flow at any cross section of the barrage is not appreciably influenced by any cross-flow from the sides except near the flanks. For 2-dimensional flow, the seepage equation may be written as:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \quad \dots (10)$$

Technique for numerical modeling of uplift pressure finite element analysis had been adopted in the present work to calculate uplift pressure under gravity dams with gallery drain and without gallery drain.

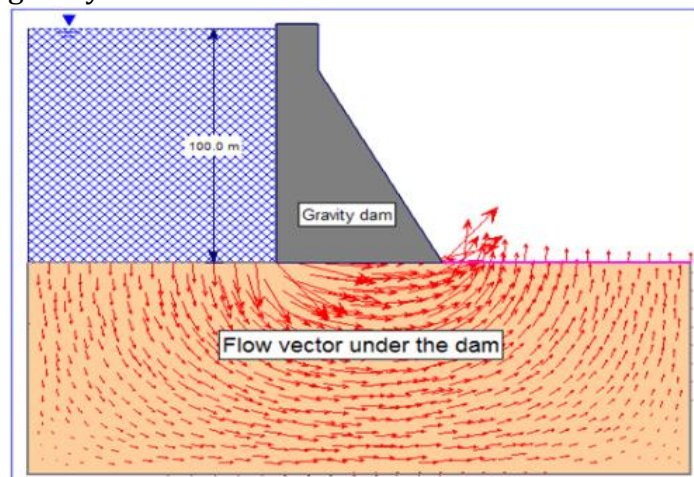


Figure 1: Flow vectors under gravity dam without drain

The influence of the hydraulics of uplift pressures underneath the base of the typical concrete gravity dam on its stability is presented. By plotting of uplift pressure distribution under the dam foundation as shown on Figures follow Can allow us to compare to the design pressure. And furthermore, the factor of safety against sliding and overturning of the dam can be checked on that particular condition. This is very important for dam safety evaluation during the dam operation.

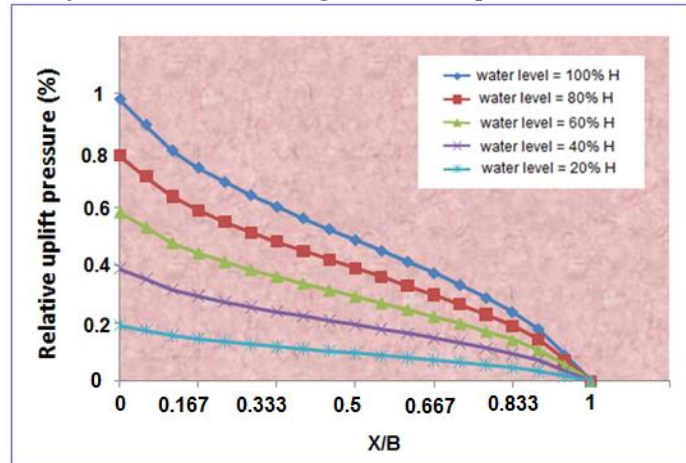


Figure 2: Uplift pressure under the base of gravity Dam without drain for different reservoir.

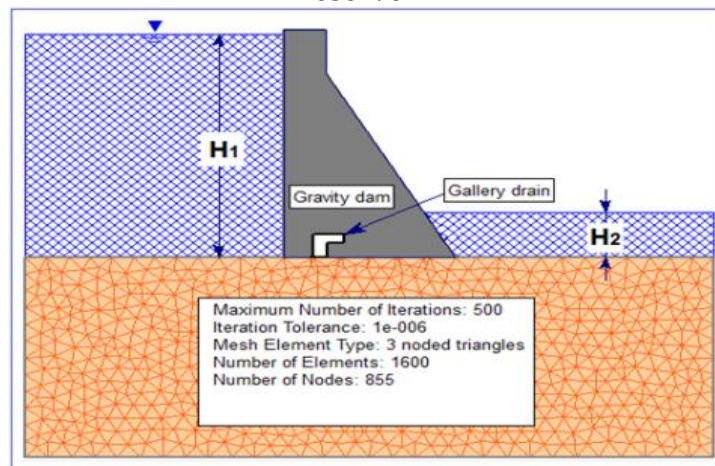


Figure 3: Total head distribution under gravity dam without drain

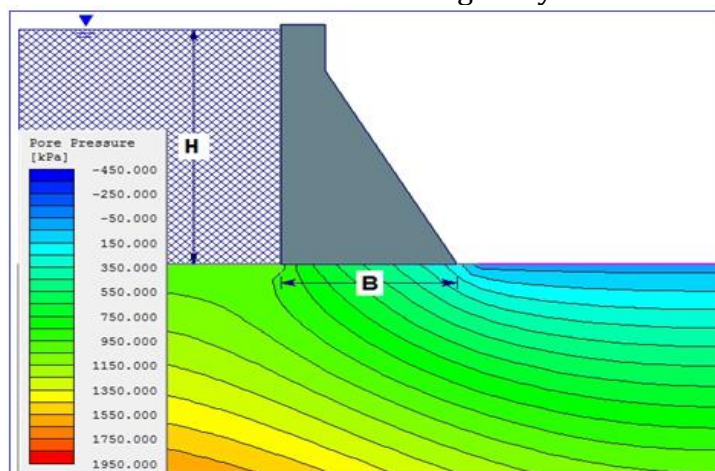


Figure 4: Pore Pressure distribution under gravity dam without drain

Table (1) Uplift pressure distribution under gravity dam without drain for different reservoir.

Distance along dam base (m)	Uplift pressure (kpa) under the base of dam for different water load H=100m				
	h=100%H	h=80%H	h=60%H	h=40%H	h=20%H
0	981	784.80	588.60	392.40	196.20
3.333	891.88	713.50	535.13	356.75	178.37
6.667	802.77	642.21	481.66	321.10	160.55
10	742.77	594.22	445.66	297.11	148.55
13.333	692.49	554.00	415.49	277.00	138.50
16.667	647.04	517.63	388.22	258.81	129.40
20	606.41	485.13	363.85	242.56	121.28
23.333	566.50	453.20	339.90	226.60	113.30
26.667	528.68	422.94	317.20	211.47	105.73
30	490.86	392.69	294.52	196.34	98.17
33.333	453.10	362.48	271.86	181.24	90.62
36.667	415.34	332.27	249.20	166.13	83.07
40	375.31	300.24	225.18	150.12	75.06
43.333	334.51	267.61	200.71	133.80	66.90
46.667	289.53	231.62	173.72	115.81	57.90
50	240.36	192.29	144.22	96.14	48.07
53.333	180.87	144.70	108.52	72.35	36.17
56.667	90.44	72.35	54.26	36.17	18.08
60	0.00	0.00	0.00	0.00	0.00

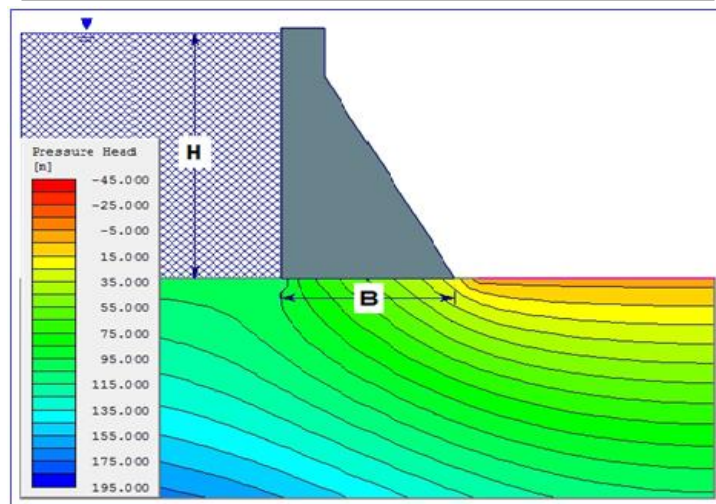


Figure 5: Pressure head distribution under gravity dam without drain
 We can calculate Uplift Force under gravity dams by using USBR which assumes uplift pressure under gravity dams is linear.

$$H_1=100 \text{ m}, H_2=0$$

$$\text{Uplift Force} = \frac{(H_1+H_2)}{2} * B * \gamma$$

$$\text{Uplift Force} = \left(\frac{100+0}{2} \right) * 60 * 9.81$$

$$= 29430 \text{ KN / m}$$

Table (2) Calculation uplift force without drain by using Finite element and USBR method for different reservoir.

H_2/H_1	Uplift force by finite element	Uplift force by USBR
0	29464.73	29430
0.1	32567.76	32373
0.2	35670.78	35316
0.3	38773.81	38259
0.4	41876.84	41202
0.5	44979.86	44145

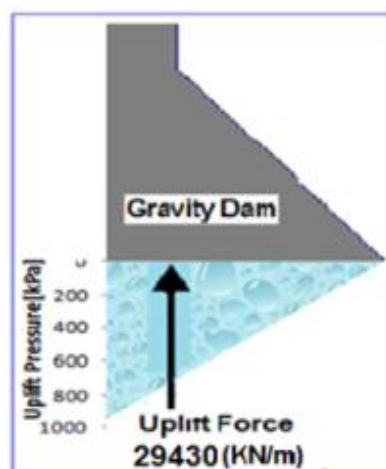


Figure 6: Uplift Force under gravity dam by using USBR

(C) Gravity Dam with Gallery Drain:

Uplift pressures beneath gravity dam model are evaluated. The drop due to drainage gallery is noticed for different locations for the drainage gallery are studied. The volume of uplift pressures in each position of the drainage gallery is calculated and compared with that in case of no drainage gallery. The reduction in volume of uplift pressures due to existing drainage gallery is found.

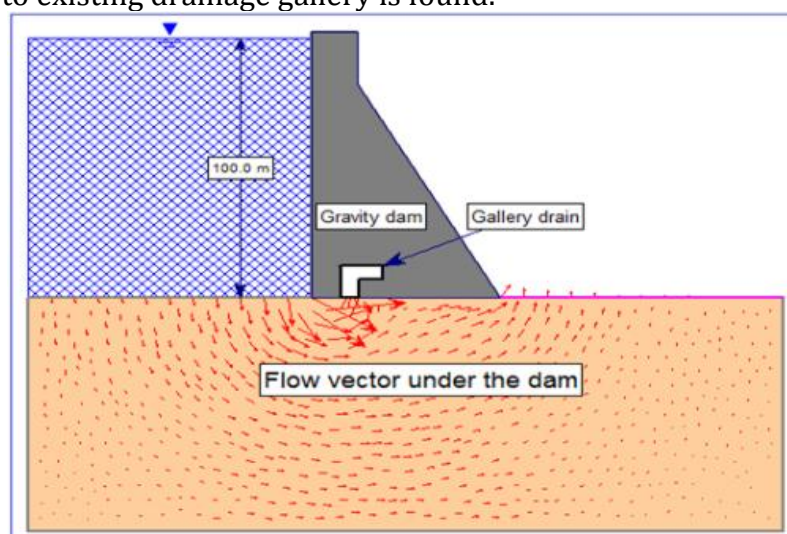


Figure 7: Flow vectors under gravity dam with drain at $X_d/B = 0.167$

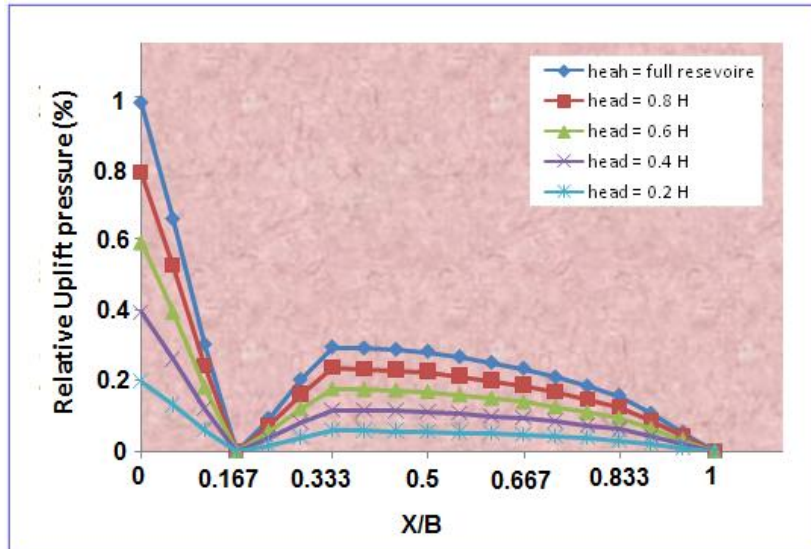


Figure 8: Uplift pressure under the base of gravity dam with drain for different reservoir at $X_d=0.167$

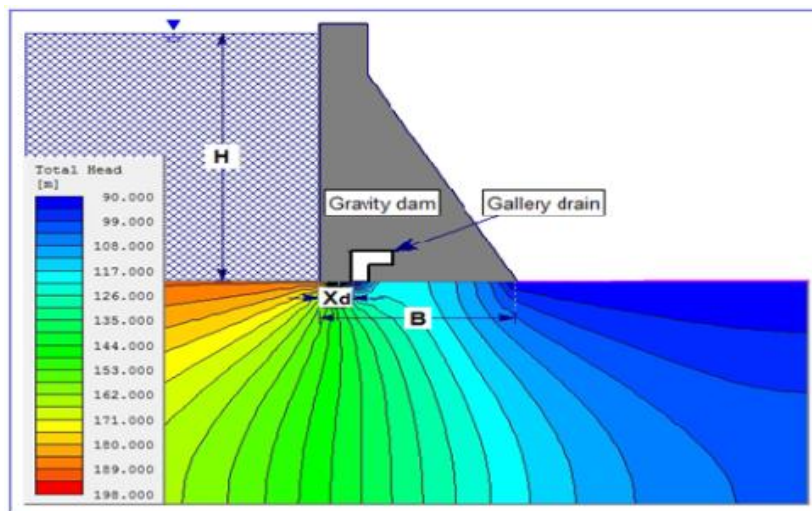


Figure 9: Total head distribution under gravity dam with drain at $X_d/B=0.167$

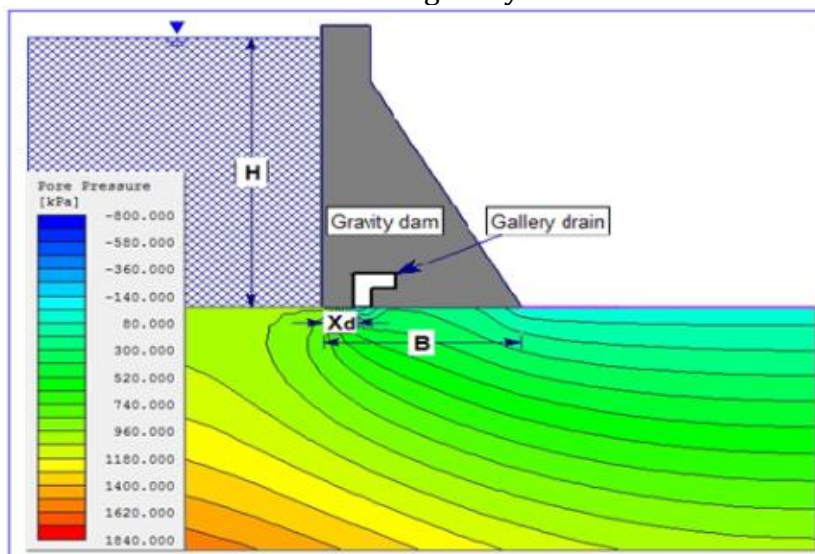


Figure 10: Pore Pressure distribution under gravity dam with drain at $X_d/B=0.167$

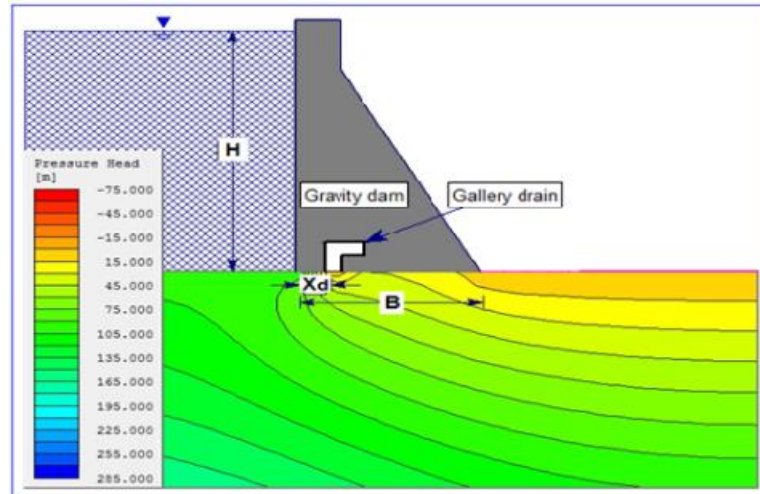
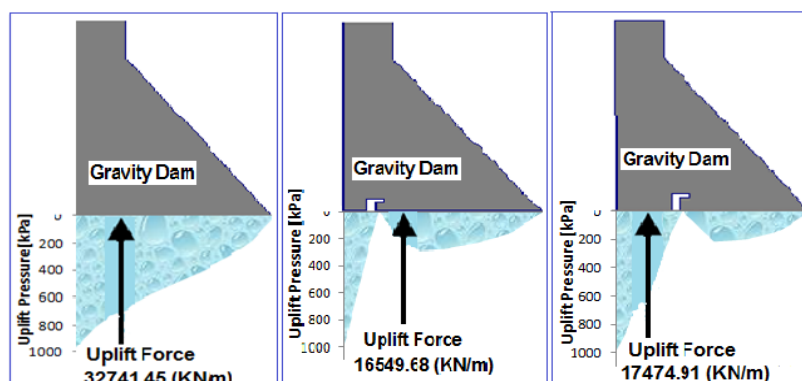


Figure 11: Pressure head distribution under gravity dam with drain at $X_d/B=0.167$
 Table 3: Uplift pressure distribution under gravity dam with drain for different drain location

Gallery Drain @ $(X/B) = 0.167$		Gallery Drain @ $(X/B) = 0.333$		Gallery Drain @ $(X/B) = 0.5$		Gallery Drain @ $(X/B) = 0.667$		Gallery Drain @ $(X/B) = 0.833$	
Distance along base (m)	Uplift pressure	Distance along base (m)	Uplift pressure	Distance along base (m)	Uplift pressure	Distance along base (m)	Uplift pressure	Distance along base (m)	Uplift pressure
0	981.00	0	981.00	0	981.00	0	981.00	0	981.00
3.33	654.00	3.33	831.85	3.33	864.83	3.33	881.77	3.33	892.64
6.67	300.48	6.67	670.61	6.67	739.25	6.67	774.49	6.67	797.12
Gallery Drain	0.00	10	517.00	10	620.60	10	673.54	10	707.39
13.33	92.07	13.33	342.90	13.33	543.91	13.33	613.70	13.33	656.22
16.67	200.39	16.67	157.54	16.67	467.70	16.67	554.78	16.67	606.06
20	292.76	Gallery Drain	0.00	20	391.35	20	496.31	20	556.51
23.33	289.70	23.33	69.32	23.33	260.21	23.33	437.51	23.33	510.80
26.67	285.73	26.67	150.88	26.67	119.56	26.67	378.22	26.67	465.13
30	280.59	30	220.37	Gallery Drain	0.00	30	317.86	30	419.37
33.33	265.20	33.33	215.70	33.33	50.39	33.33	210.97	33.33	370.03
36.67	249.20	36.67	210.01	36.67	109.67	36.67	96.930	36.67	320.15
40	232.64	40	203.27	40	160.67	Gallery Drain	0.00	40	269.67
43.33	208.11	43.33	184.16	43.33	151.70	43.33	34.10	43.33	179.24
46.67	182.72	46.67	163.92	46.67	140.42	46.67	74.22	46.67	82.35
50	156.19	50	142.38	50	127.32	50	106.19	Gallery Drain	0.00
53.33	106.13	53.33	96.88	53.33	86.88	53.33	73.026	53.33	0.00
56.67	53.06	56.67	48.44	56.67	43.44	56.67	36.51	56.67	0.00
60	0.00	60	0.00	60	0.00	60	0.00	60	0.00



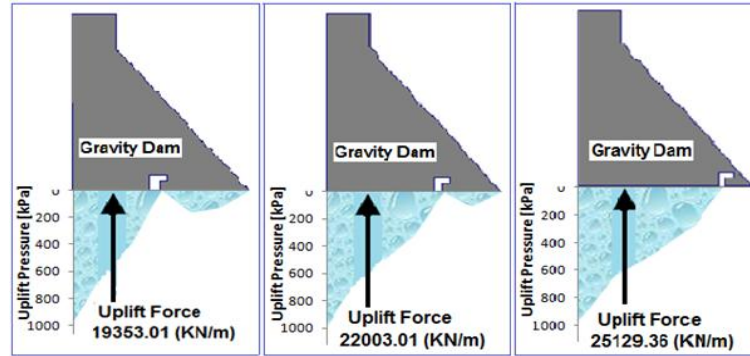


Figure 12: Uplift Force under gravity dam for different drain location

From the above, it can be observed that the gallery drain at first location reduces maximum uplift pressure under the base of dam, where drain reduction factor can be calculated as follow:

$$\text{DRF} = \frac{(\text{uplift force without drain} - \text{uplift force with drain})}{\text{uplift force without drain}}$$

$$\text{DRF} = \frac{(32741.45 - 16549.68)}{32741.45} = 0.507$$

4. Drain Reduction Factors (DRF) for Different Reservoir and Drain Location:

The optimum location of the drainage gallery underneath gravity dam is the goal of this study. This location is denoted by position of maximum reduction in uplift force (DRF). Table below are present percentage of average reduction in volume of uplift pressures for different cases.

Table 4: Percentage of average reduction in volume of uplift pressures due to gallery drain beneath gravity dam (DRF)

Drain No.	Relative drainage position X_d/B	H_2/H_1						Average percentage
		No tail	0.1	0.2	0.3	0.4	0.5	
		Percentage of reduction in volume of uplift pressure due to gallery drain beneath gravity dam						
1	0.167	0.494	0.486	0.458	0.434	0.414	0.397	0.4493
2	0.333	0.466	0.447	0.432	0.420	0.409	0.400	0.4291
3	0.500	0.408	0.388	0.387	0.385	0.384	0.383	0.3891
4	0.667	0.328	0.307	0.319	0.329	0.338	0.345	0.3278
5	0.833	0.232	0.201	0.226	0.247	0.265	0.280	0.2418

It can observe that, gallery drain minimizes uplift pressures beneath gravity dam with different values according to the relative position of the gallery drain. Positions of the drainage gallery are carried out for different locations and the following conclusions are made:

- ✓ The optimum position of the drainage gallery, constructed beneath gravity dam, is found at $X_d/B = 0.167$ at which reduction in volume of the uplift pressures is maximum and equals about 0.494.
- ✓ The optimum position of the drainage gallery can be achieved at $X_d/B = 0.167$, at which seepage discharge entering the drainage gallery is maximum.

Comparisons between galleries drain and sheet pile. On Reduction Factors for different reservoir conditions in this part, we can observe that the values of drain reduction factors (DRF) are greater than values of sheet reduction factors (SRF) which

mean that the gallery drain minimizes the uplift force under gravity dams greater than sheet pile. Table (5) shows that maximum reduction in sheet pile is at no tail where $X/B=0.125$, that is similar to gallery drain.

Table 5: Percentage of average reduction in volume of uplift pressures due to sheet pile beneath gravity dam (SRF)

Sheet pile No.	Relative sheet pile position Xs/B	$H2/H1$						Average percentage
		No tail	0.1	0.2	0.3	0.4	0.5	
		Percentage of reduction in volume of uplift pressure due to sheet pile beneath gravity dam						
1	0.125	0.295	0.249	0.2	0.161	0.127	0.098	0.188
2	0.25	0.199	0.161	0.129	0.104	0.082	0.063	0.123
3	0.5	0.037	0.003	0.001	0.001	0.001	0	0.007
4	0.75	-	-	-	-	-	-	-
5	0.875	-	-	-	-	-	-	-

5. Conclusion:

The following main conclusions can be drawn from the results which are based on uplift pressure under the gravity dams with gallery drain and without gallery drain for different reservoir and drain location:

- ✓ The SLIDE V.5.0, computer program is suitable to modeling a complex geometry of foundation system than other applicable methods; the modeling is very close to the realities of the verified case.
- ✓ The values of drain reduction factor (DRF) increases for the following reasons, listed according to their importance: (a) Location, Drain nearest the upstream side at $X_d/B = 0.167$ which make the maximum (DRF) close to 0.4493. (b) Reservoir condition, Drain nearest the upstream side at $X_d/B = 0.167$ which make the maximum (DRF) close to 0.494, when water is full up on the upstream side and there is no water on the downstream side.
- ✓ The optimum position of the drainage gallery can be achieved at $X_d/B = 0.167$, at which seepage discharge entering the drainage gallery is maximum.
- ✓ Uplift force calculated by finite element method showed differ from the very convenient way presented by (USBR) of estimating uplift pressures under concrete dams since they require only very simple calculations to achieve their objective.
- ✓ Uplift pressure under the dam are nonlinear variation from maximum value near upstream side reach to minimum value in downstream side and full depending of the value of water load condition (reservoir water level)
- ✓ Mesh independents solution by finite element method it required to select the optimum number of element to make the results more accurate.

6. Acknowledgment:

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