Research Title:

Variation of Uplift Pressure and Exit Gradient Downstream of Hydraulic Structures

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Variation of Uplift Pressure and Exit Gradient Downstream of Hydraulic Structures

Abstract:

In this research the variation of uplift pressure under the structure foundation and the exit gradient downstream of the structure were investigated. The analysis was done using a Finite Element modeling with the aid of the Geo-studio software.

The results of analysis of exit gradient variation indicate that the maximum exit gradient near the toe of the structure is observed when the ratio of the length of upstream cutoff to the length of downstream cutoff (S1/S2 = 1). This maximum value of the exit gradient will decrease as the ratio of (S1/S2) increased. Moreover, it was observed that the exit gradient exhibits little variation with the ratio of (S1/S2) beyond a distance of (x/B = 0.3) from the toe of the structure. Science, the slope of variation decreases with the increase of x/B.

The analysis indicate also that the highest length of protection required at the downstream side as at (x/B = 0.25). In addition to that it was also observed that the effect of length of the downstream cutoff (S2) on the exit gradient is demolished beyond a distance of (x/B = 0.3).

The analysis of the uplift pressure variation indicate that all the pressure values were enveloped by two limit in curves, the upper one is the minimum selected (S1/S2) ratio of (0.25) and the lower curve is for the maximum (S1/S2) ratio of (0.3). The value of the pressure for the other (S1/S2) ratios was falling between these two envelope curves.

Moreover, it was found that the maximum pressure to total head ratio, occurs at the heel of the structure is approximately (0.918), while the minimum ratio occurs at the end of the floor which is approximately (0.75). In addition to that, it was observed that the analysis indicates that the value of upstream cutoffs has considerable effect on decreasing the uplift pressure, especially from a value of (1m to 2m).

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LIST OF SYMBOLS

Note: most of the symbols used are listed below, others are defined where they appeared in this study.

Symbol	*Definition*	*Unit*
S1	length of the upstream cutoff	L
S2	length of the downstream cutoff	L
B	length of the floor of the foundations	L
L	Length of required protection at the downstream of the structure	L
V	Volume of the superstructure	L^3
H	difference in head between the upstream and downstream sides of the hydraulic structure	L
D	depth of impervious layer	L
i_c	Critical Exit Gradient	Dimensionless
i_e or i_{exit}	Exit Gradient	Dimensionless
γ_w	Unit Weight of water	$M/L^2\ T^2$
γ_{sub}	Submerged weight of the grain at the exit	$M/L^2\ T^2$
q	Discharge per 1m Length	$L^3/T.L$
Δh	Head Lost between two equipotential lines	L
l	Length between two points	L
v	Discharge Velocity	L/T
i	Hydraulic Gradient	Dimensionless
k	Coefficient of Permeability	L/T
ρ	Mass Density of the Fluid	M/L^3
g	Acceleration due to Gravity	L/T^2
μ	Absolute viscosity of the fluid	M/L.T

Symbol	***Definition***	***Unit***
υ_s	Actual Velocity of Seepage Through the Soil	L/T
n	Porosity of the Soil	Dimensionless
R_n	Reynolds number	Dimensionless
K_x	Permeability in x-direction	L/T
k_y	Permeability in y-direction	L/T
kr	Ratio of Permeability in x-direction to Permeability in y-direction	Dimensionless
ψ	Streamline Function	L^2/T
Φ	Equipotential function	L^2/T
L	Length of Seepage Path	L
x_t	Scale Factor	Dimensionless
Q	Discharge or Seepage flow	L^3/T
G_s	Specific Gravity of Soil	Dimensionless
e	Void Ratio	Dimensionless
Fs	Factor of Safety	Dimensionless
FS_G	Factor of Safety for Escape Gradient	Dimensionless
γ_c	Unit Weight of Concrete	$M/L^2\ T^2$

Introduction:

Water Resources are nowadays important to be controlled in the view of limited available water in accordance with the increasing demand for water.

Hydraulic structures such as Dams, Reservoirs, Barrages, Weirs …………., etc. are those structures used for controlling water resources. The hydraulic engineer should carefully design these hydraulic structures such that it can perform its function safely. The most critical aspect of the design of such structures is the design concerning its foundation. Many failures had been reported in literature due to either foundation failure or due to overall stability of the structure.

The most critical aspects that the designer should take into account are the failure due to uplift pressure and / or piping phenomenon at the toe of the structure. Proper factor of safeties should be adopted for both aspects. These factors of safeties depend on many parameters such as the type of the structure, its size and importance, the type of soil beneath the structure and the level of the risk occurs if failures happen. Values of these factors were suggested by some pioneers in literature.

In order to provide the required factor safety against both uplift pressure and piping due to exit gradient, the designers usually provide cutoffs at the upstream and the downstream sides of the foundation of the hydraulic structures. The upstream cutoffs in general decreases the uplift pressure and exit gradient, however, they reduces the uplift pressure in a rate more than that for the exit gradient. In order to control the exit gradient, a downstream cutoff should be provided, which has direct effect on the exit gradient. The designer should decide the depth of both cutoffs so as to achieve the required factor of safeties. Increasing the depths of the downstream cutoffs will impose significant reduction in the exit gradient while increasing the uplift pressure.

In this research the variation of uplift pressure under the structure foundation and the exit gradient downstream of the structure were investigated. The analysis was done using a Finite Element modeling with the aid of the Geo-studio software.

These variations are affected by different variables, some of these variables are given by the curve under consideration, such as, the maximum difference in head between the upstream and downstream sides of the structure, the soil permeability, the depth of impervious layer (D) and the degree of anisotropy. The other variables are to be selected by the designers, such as, the length of the floor of the foundation (B), the length of the upstream cutoffs (S_1) and the length of the downstream cutoffs (S_2).

Figure (1) shows a schematic representation of a typical hydraulic structure.

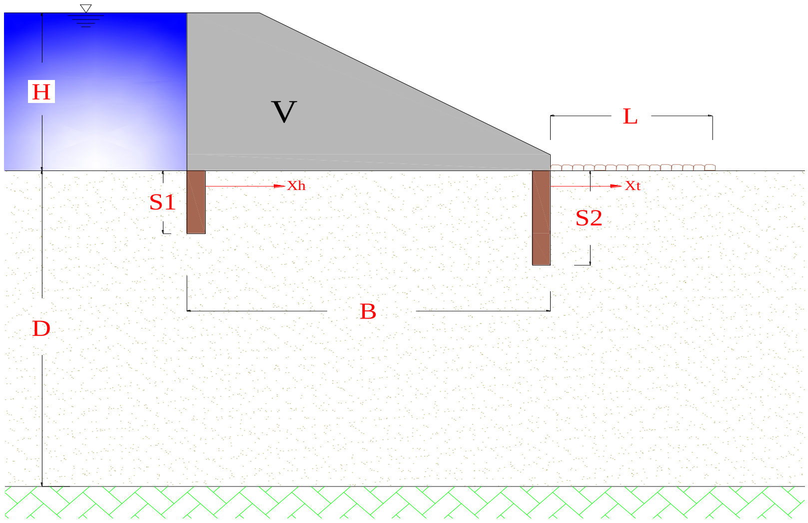

Fig (1): Schematic Representation of a Typical Hydraulic Structure.

As mentioned above the variations of both uplift pressure and exit gradient are investigated using Geo-studio finite element modeling.

Theory

To design a safe hydraulic structure against seepage, the following two important points must be considered.

(a) Safety against Uplift Pressure

The water seeping below the hydraulic structure exerts an uplift pressure on the floor. 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. If the thickness of floor is insufficient, its weight would be inadequate to resist the uplift pressure. This may ultimately lead to bursting of the floor, and thus failure of the hydraulic structure may occur.

(b) Safety against Piping

Exit gradient is usually considered as a measure of the effect of the piping phenomenon. Piping occurs if the exit hydraulic gradient at the downstream point approaches the critical hydraulic gradient. The exit gradient is said to be critical when the upward disturbing force on the grain is just equal to the submerged weight of the grain at the exit. Terzaghi defined i_{cr} as $i_{cr} = \frac{\gamma_{sub}}{\gamma_w}$

Basic seepage equations:

In order to obtain a fundamental relation for the quantity of seepage through a soil mass under a given condition, consider the case shown in Figure (2). The cross-sectional area of the soil is equal to (A) and the rate of seepage is (q).

According to Bernoulli's theorem, the total head for flow at any section in the soil can be given by:

Total head=elevation head + pressure head + velocity head (1)

The velocity head for flow through soil is very small and can be neglected.

The total heads at sections A and B can thus be given by:

Total head at A = $z_A + h_A$
Total head at B = $z_B + h_B$

Where: z_A and z_B are the elevation heads and h_A and h_B are the pressure heads. The loss of head Δh between sections A and B is:

$$\Delta h = (z_A + h_A) - (z_B + h_B) \tag{2}$$

The hydraulic gradient *i* can be written as:

$$i = \frac{\Delta h}{L} \tag{3}$$

where: L is the distance between sections A and B.

Darcy (1856) published a simple relation between the discharge velocity and the hydraulic gradient:

$$v = ki \tag{4}$$

where: v = discharge velocity
i = hydraulic gradient
k = coefficient of permeability

Hence the rate of seepage q can be given by:

$$q = k\,i\,A \tag{5}$$

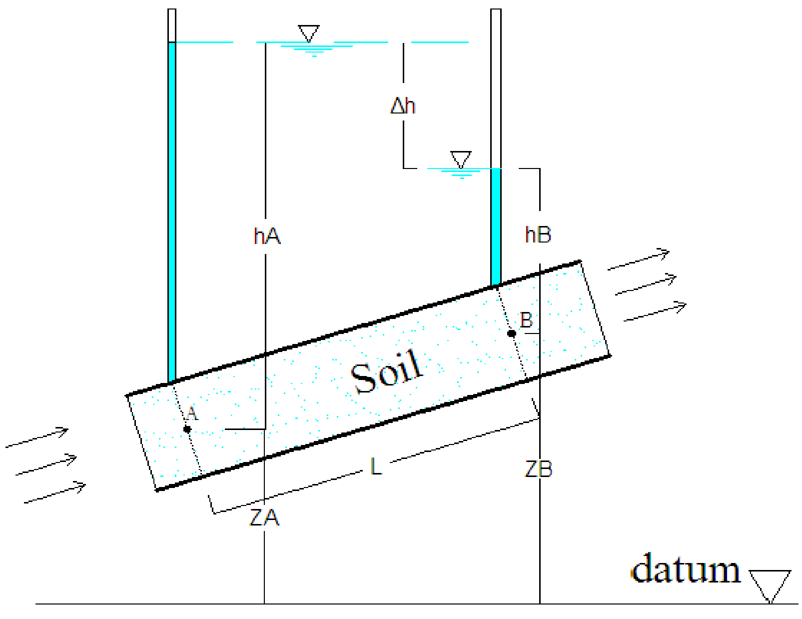

Fig (2) Development of Darcy's law. (Das, 2008)

Note that A is the cross-section of the soil perpendicular to the direction of flow.

The coefficient of permeability k has the units of velocity, such as cm/s or mm/s, and is a measure of the resistance of the soil to flow of water. When the properties of water affecting the flow are included, we can express k by the relation:

$$k(cm/s) = \frac{K\rho g}{\mu} \quad (6)$$

where:
K = intrinsic (or absolute) permeability, cm^2
ρ = mass density of the fluid, g/cm^3
g = acceleration due to gravity, cm/s^2
μ = absolute viscosity of the fluid, poise [that is, g/(cm.s)]

It must be pointed out that the velocity given by Eq. (4) is the discharge velocity calculated on the basis of the gross cross-sectional area. Since water can flow only through the interconnected pore spaces, the actual velocity of seepage through soil, v_s, can be given by:

$$v_s = \frac{v}{n} \quad (7)$$

where: (n) is the porosity of the soil.

Some typical values of the coefficient of permeability are given in Table (1). The coefficient of permeability of soils is generally expressed at a temperature of 20°C.

Table (1) Typical coefficient values of permeability for various soils

Material	Coefficient of permeability (mm/s)
Coarse	$10 – 10^3$
Fine gravel, coarse, and medium sand	$10^{-2} – 10$
Fine sand, loose silt	$10^{-4} – 10^{-2}$
Dense silt, clayey silt	$10^{-5} – 10^{-4}$
Silty clay, clay	$10^{-8} – 10^{-5}$

Validity of Darcy's law:

Darcy's law given by Eq. (4), $v = ki$ is true for laminar flow through the void spaces. Several studies have been made to investigate the range over which Darcy's law is valid, and an excellent summary of these works was given by Muskat (1937). A criterion for investigating the range can be furnished by the Reynolds number. For flow through soils, Reynolds number R_n can be given by the relation:

$$R_n = \frac{v\, D\, \rho}{\mu} \qquad (8)$$

where:

v = discharge (superficial) velocity, cm/s

D = average diameter of the soil particle, cm

ρ = density of the fluid, g/cm3

μ = coefficient of viscosity, g/(cm. s).

For laminar flow conditions in soils, experimental results show that:

$$R_n = \frac{v\, D\, \rho}{\mu} \leq 1 \qquad (9)$$

Conclude that, for flow of water through all types of soil (sand, silt, and clay), the flow is laminar and Darcy's law is valid. With coarse sands, gravels, and boulders, turbulent flow of water can be expected, and the hydraulic gradient can be given by the relation:

$$i = av + bv^2 \qquad (10)$$

where: (a) and (b) are experimental constants.

Darcy's law, as defined by Equation (4), implies that the discharge velocity bears a linear relation with the hydraulic gradient. Hansbo (1960) reported the test results of four undisturbed natural clays. On the basis of his results

$$v = k(i - i') \qquad i \geq i' \qquad (11)$$

$$v = k\, i^n \qquad i < i' \qquad (12)$$

The value of (n) for the four Swedish clays was about (1.6). There are several studies, however, that refute the preceding conclusion.

Two - Dimensional seepage equation:

The general case of seepage in two dimensions will now be considered. Initially it will be assumed that the soil is homogeneous and isotropic with respect to permeability. Two-dimensional steady flow of the incompressible pore fluid is governed by Laplace's equation which indicates simply that any imbalance in flows into and out of an element in the x direction must be compensated by a corresponding opposite imbalance in the y direction. Laplace's equation can be solved graphically, analytically, numerically, or analogically.

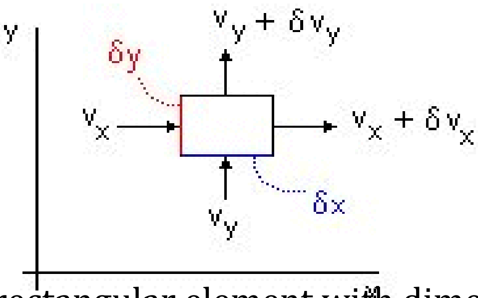

Figure (3) rectangular element with dimensions δx, δy (Harr, 1962)

For a rectangular element with dimensions δx, δy and unit thickness, in the x direction the velocity of flow into the element is:

$$\boldsymbol{V_x = -k\,\frac{\partial h}{\partial x}} \qquad (13)$$

The negative sign being required because flow occurs down the hydraulic gradient. The velocity of flow out of the element is:

$$V_x + \delta V_x \;=\; -k\left(\frac{\partial h}{\partial x} + \frac{\partial^2 h}{\partial x^2}\,\delta x\right) \qquad (14)$$

Similar expressions can be written for the y direction. Balance of flow requires that:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \qquad (15)$$

and this is Laplace's equation. In three dimensions, Laplace's equation becomes:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \quad (16)$$

Seepage equation for homogeneous isotropic medium:

The seepage underneath hydraulic structure may be represented by:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \quad (16)$$

This is known as Laplace equation for seepage of water through porous media. This equation implicitly assumes that:

(i) the soil is homogeneous and isotropic;

(ii) the voids are completely filled with water;

(iii) no consolidation or expansion of soil takes place; and

(iv) flow is steady and obeys Darcy's law.

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:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \quad (15)$$

Seepage equation for homogeneous anisotropic medium:

It will now be assumed that the soil, although homogeneous, is anisotropic with respect to permeability. Most natural soil deposits are anisotropic, with the coefficient of permeability having a maximum value in the direction of stratification and a minimum value in the direction normal to that of stratification; these directions are denoted by x and z, respectively, i.e.

$$k_x = k_{max} \qquad \text{and} \qquad k_z = k_{min}$$

in this case the generalized form of Darcy's law is:

$$v_x = k_x i_x = -\, k_x \frac{\partial h}{\partial x} \qquad (13)$$

$$v_z = k_z i_z = -\, k_z \frac{\partial h}{\partial z}$$

Also, in any direction s, inclined at angle to the x direction, the coefficient of permeability is defined by the equation:

$$v_s = -k_s \frac{\partial h}{\partial s}$$

now

$$\frac{\partial h}{\partial s} = \frac{\partial h}{\partial x}\frac{\partial x}{\partial s} + \frac{\partial h}{\partial z}\frac{\partial z}{\partial s}$$

i.e.

$$\frac{v_s}{k_s} = \frac{v_x}{k_x}\cos\alpha + \frac{v_z}{k_z}\sin\alpha \qquad (17)$$

The components of discharge velocity are also related as follows:

$$v_x = v_s \cos\alpha \qquad (18)$$

$$v_z = v_s \sin\alpha \qquad (19)$$

Hence,

$$\frac{l}{k_s} = \frac{\cos^2\alpha}{k_x} + \frac{\sin^2\alpha}{k_z}$$

Or

$$\frac{s^2}{k_s} = \frac{x^2}{k_x} + \frac{z^2}{k_z}$$

Given the generalized form of Darcy's law, the equation of continuity can be written:

$$k_x \frac{\partial^2 h}{\partial x^2} + k_z \frac{\partial^2 h}{\partial z^2} = 0$$

or

$$\frac{\partial^2 h}{(k_z/k_x)\partial x^2} + \frac{\partial^2 h}{\partial z^2} = 0$$

Substituting

$$x_t = x\sqrt{\frac{k_z}{k_x}} \quad . . . . \quad \text{(Scale factor)} \qquad (20)$$

The equation of continuity becomes:

$$\frac{\partial^2 h}{\partial x_t^2} + \frac{\partial^2 h}{\partial z^2} = 0 \qquad (21)$$

Which is the continuity equation for an isotropic soil in an x_t-z plane?

Thus, Equation (20) defines a scale factor which can be applied in the x direction to transform a given anisotropic flow region into a fictitious isotropic flow region in which the Laplace equation is valid. Once the flow net (representing the solution of the Laplace equation) has been drawn for the transformed section the flow net for the natural section can be obtained by applying the inverse of the scaling factor. Essential data, however, can normally be obtained from the transformed section. The necessary transformation could also be made in the z direction.

Seepage equation for non- homogeneous anisotropic medium:

Two isotropic soil layers of thicknesses H_1 and H_2 are shown in Figure (4), the respective coefficients of permeability being k_1 and k_2; the boundary between the layers is horizontal. (If the layers are anisotropic, k_1 and k_2 represent the equivalent isotropic coefficients for the layers.) The two layers can be considered as a single homogeneous anisotropic layer of thickness (H_1+H_2) in which the coefficients in the directions parallel and normal to that of stratification are k_x and k_z, respectively.

For one-dimensional seepage in the horizontal direction, the equipotentials in each layer are vertical. If h_1 and h_2 represent total head at any point in the respective layers, then for a common point on the boundary

$h_1 = h_2$. Therefore, any vertical line through the two layers represents a common equipotential. Thus, the hydraulic gradients in the two layers, and in the equivalent single layer, are equal; the equal hydraulic gradients are denoted by i_x.

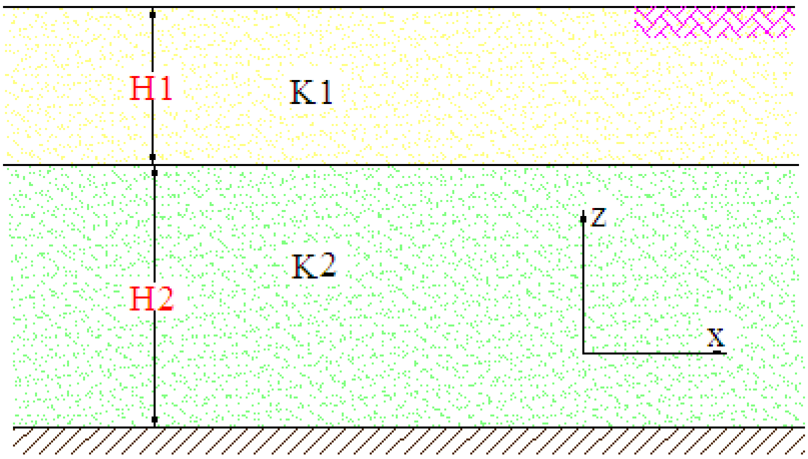

Figure (4) Non-homogeneous soil conditions (Craig, 2005)

The total horizontal flow per unit time is given by:

$$q_x = (H_1 + H_2)k_x i_x = (H_1 k_1 + H_2 k_2) i_x \quad (22)$$

$$\therefore \quad k_x = \frac{H_1 k_1 + H_2 k_2}{H_1 + H_2} \quad (23)$$

For one-dimensional seepage in the vertical direction, the discharge velocities in each layer, and in the equivalent single layer, must be equal if the requirement of continuity is to be satisfied. Thus:

$$v_x = k_z i_z = k_1 i_1 = k_2 i_2$$

where i_z is the average hydraulic gradient over the depth ($H_1 + H_2$). Therefore:

$$i_1 = \frac{k_z}{k_1} i_z \quad \text{, and} \quad i_2 = \frac{k_z}{k_2} i_z$$

Now the loss in total head over the depth ($H_1 + H_2$) is equal to the sum of the losses in total head in the individual layers, i.e.

$$i_z\,(H_1 + H_2) = i_1\,H_1 + \,i_2\,H_2$$

$$= k_z\,i_z\,(\frac{H_1}{k_1} + \frac{H_2}{k_2})$$

$$\therefore \quad k_z = \frac{H_1+H_2}{\left(\frac{H_1}{k_1}\right)+\left(\frac{H_2}{k_2}\right)} \qquad (24)$$

Similar expressions for k_x and k_z apply in the case of any number of soil layers. It can be shown that k_x must always be greater than k_z, i.e. seepage can occur more readily in the direction parallel to stratification than in the direction perpendicular to stratification.

Calculation of uplift pressure and exit gradient:

The uplift pressure at any point under the structure will be dependent on the presence, location, and effectiveness of foundation drains. Cutoffs such as grout curtains, impervious blankets, sheet-pile walls, and cutoffs also affect uplift pressures and should be considered in determining design uplift pressures and drainage requirements. Seepage flow net and creep theory can be used to determine uplift pressures for structures on soil foundations. Uplift pressure is an applied force that must be included in the stability and stress analysis. The uplift pressure will be considered as acting over (100) percent of the base. Uplift pressures are assumed to be unchanged by earthquake loads. Uplift assumptions are valid only if there is adequate resistance to piping. If there is a concern about piping, geotechnical engineers should be consulted.

Where seepage occurs, the pressure heads at points of interest must be obtained from a seepage analysis. Where soil conditions adjacent to and below a structure can be assumed homogeneous (or can be mathematically transformed into equivalent homogeneous conditions), simplified methods such as the line-of-seepage method may be used. However, designers should ensure that water pressures are based on appropriate consideration of actual soil conditions. The line-of-seepage method is illustrated in Figure (5). The uplift pressures at the ends of the base (points B and C) are estimated by assuming that the head varies linearly along the shortest possible seepage path (ABCD). Where a cutoff is present Figure (6), point B is at the bottom of the cutoff, and line BC is drawn diagonally. Permeability that is different in the horizontal and vertical directions can be handled by adjusting the length of the different segments along the total seepage path in accordance with the relationship between this different permeability.

L = total length of seepage path = L_B + a + L_C,

h = head difference across wall,

U_B = water pressure at B = [L_B - $\frac{h*L_B}{L}$]γ_w ,

UC = water pressure at C = [L_B - $\frac{h}{L}$ $(L_B + a)$]γ_w

Where:

γ_w= the unit weight of water.

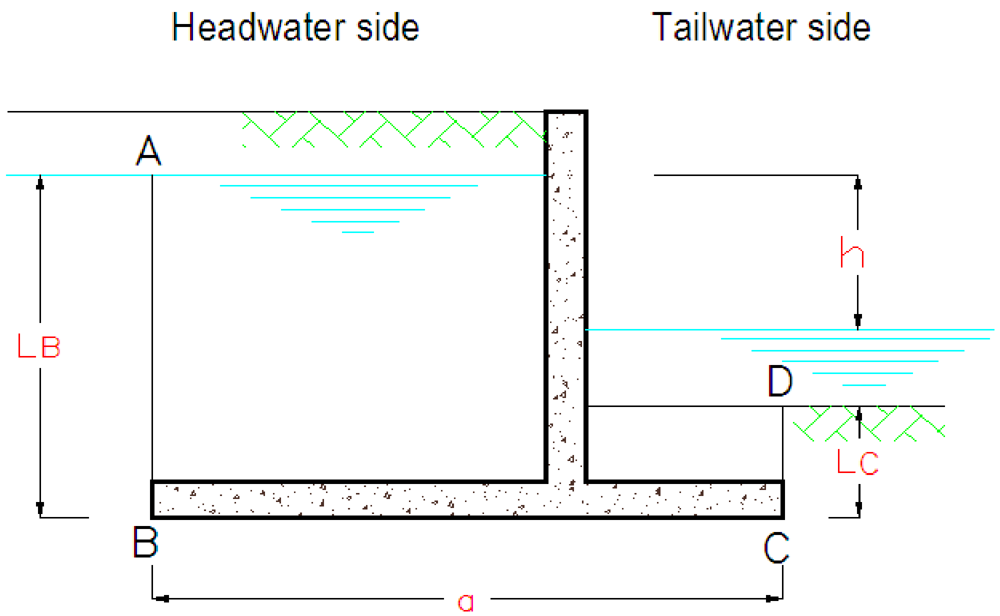

Figure (5) Line of seepage method for water pressures

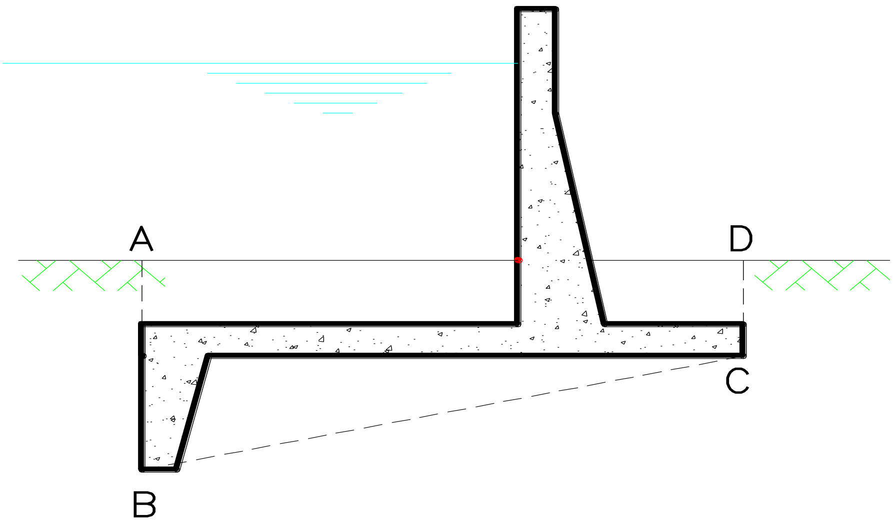

Figure (6) Seepage path for wall with upstream cutoff

Cutoffs can also contribute to reducing uplift below structures. Cutoffs can be grout curtains, concrete trenches, steel sheet piling, or impervious blankets. The effectiveness of cutoffs, however, can be jeopardized by leakage through joints, cracks, and fractures. Therefore, drains are considered to be the most reliable and cost-effective way of reducing foundation- uplift pressures, especially for structures founded on rock. Although grout curtain cutoffs are commonly used in combination with drainage systems for dams founded on rock, the grout-curtain cutoff helps more to reduce drain flows in the drainage gallery than to reduce uplift pressures.

Escape and Critical Gradients:

The escape or exit gradient, i_e , is the rate of dissipation of head per unit of length in the area where seepage is exiting the porous media. For confined flow, the area of concern is usually along the uppermost flow line near the flow exit, e.g., at the downstream edge of a concrete or other impermeable structure.

Escape gradients for flow through embankments may also be studied by choosing squares from the area of interest in the flow net (usually at or near the exit face and downstream toe) and calculating gradients. If the gradient is too great where seepage is exiting, soil particles may be removed from this area.

This phenomenon, called flotation, can cause piping (the removal of soil particles by moving water) which can lead to undermining and loss of the structure. The gradient at which flotation of particles begins is termed the critical gradient, i_{cr}. Critical gradient is determined by the in-place unit weight of the soil and is the gradient at which upward drag forces on the soil particles equal the submerged weight of the soil particles.

The critical gradient is dependent on the specific gravity and density of the soil particles and can be defined in terms of specific gravity of solids, G_s, void ratio, e, and porosity, n:

$$i_{cr} = \frac{\gamma'_m}{\gamma_w} = \frac{G_s\,(1-n)\gamma_w + n\gamma_w - \gamma_w}{\gamma_w} \qquad (25)$$

$$i_{cr} = G_s\,(1-n)\gamma_w + n\gamma_w - \gamma_w$$

$$i_{cr} = G_s\,(1-n) + n - 1$$

$$i_{cr} = G_s\,(1-n) - (1-n)$$

$$i_{cr} = (G_s - 1)(1-n)$$

since $e = \frac{n}{1-n}$ and $n = \frac{e}{1+e}$ (26)

$$i_{cr} = (G_s - 1)(\frac{n}{e})$$

$$i_{cr} = (G_s - 1)(\frac{\frac{e}{1+e}}{e})$$

$$i_{cr} = \frac{(G_s-1)}{(1+e)} \qquad (27)$$

If typical values of G_s, *e*, and *n* for sand are used in the above equations, i_{cr} will be approximately 1. Investigators have recommended ranges for factor of safety for escape gradient, [$FS_G = \frac{i_{cr}}{i_e}$] from 1.5 and

15, depending on knowledge of soil and possible seepage conditions. Generally, factors of safety in the range of 4-5 (Harr 1962, 1977) or 2.5-3 (Cedergren 1977) have been proposed.

Safety of hydraulic structures against piping:

When upward seepage occurs and the hydraulic gradient i is equal to i_{cr}, *piping* or *heaving* originates in the soil mass:

$$i_{cr} = \frac{\gamma'}{\gamma_w}$$

$$\gamma' = \gamma_{sat} - \gamma_w = \frac{G_s\,\gamma_w + e\,\gamma_w}{1+e} - \gamma_w = \frac{(G_s - 1)\gamma_w}{1+e}$$

so, $$i_{cr} = \frac{\gamma'}{\gamma_w} = \frac{G_s - 1}{1+e} \qquad (28)$$

For the combinations of (Gs) and e generally encountered in soils, i_{cr} varies within a range of about (0.85–1.1).

Harza, (1935) investigated the safety of hydraulic structures against piping. According to his work, the factor of safety against piping, Fs, can be defined as:

$$\text{Fs} = \frac{i_{cr}}{i_{exit}} \qquad (29)$$

Where (i_{exit})is the maximum exit gradient. The maximum exit gradient can be determined from the flow net. Referring to Figure (7), the maximum exit gradient can be given by $\Delta h/l$ (Δh is the head lost between the last two equipotential lines and l the length of the flow element). A factor of safety of (3 – 4) is considered adequate for the safe performance of the structure.

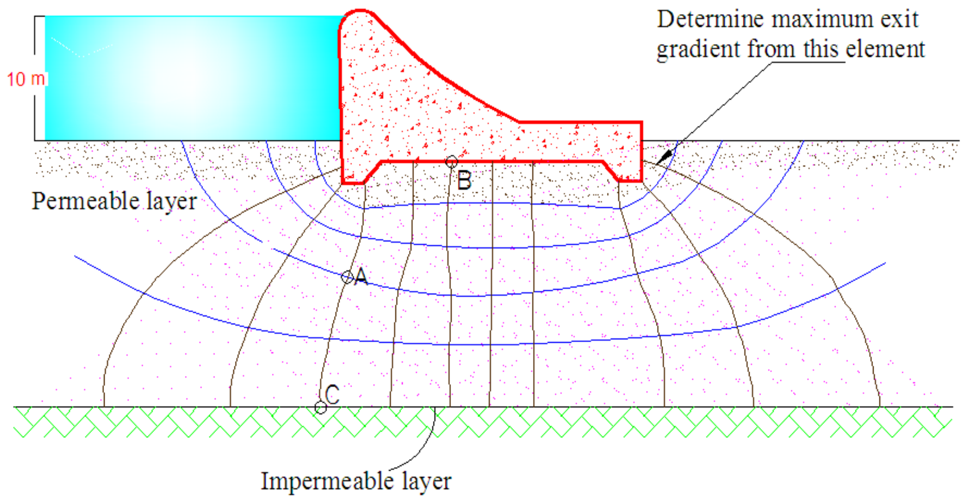

Figure (7) *Flow net under a dam*, (Harza ,1935)

Harza also presented charts for the maximum exit gradient of dams constructed over deep homogeneous deposits (Figure 8), the maximum exit gradient can be given by:

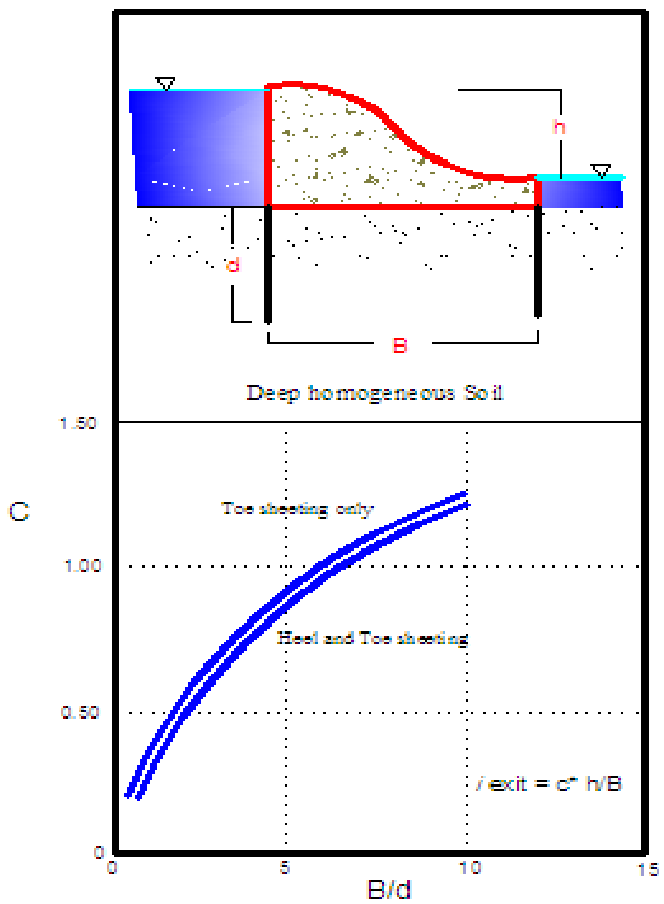

Figure (8) Critical exit gradients, (Harza ,1935)

$$i_{exit} = C\ \frac{h}{B} \tag{30}$$

A theoretical solution for the determination of the maximum exit gradient for a single row of sheet pile structures is available and is of the form:

$$i_{exit} = \frac{1}{\pi}\ \frac{maximum\ hydraulic\ head}{depth\ of\ penetration\ of\ sheet\ pile} \tag{31}$$

Result and Discussion:

Exit gradient variation along the downstream side of the structure:

This distribution was investigated due to its importance for deciding the length of protection required to protect this soil side from piping failure, the length of this protection (L), which is a kind of apron, riprap or pitching, is decided upon providing a minimum factor of safety of (3). This will reflect a maximum value of exit gradient of (1/3), since this factor of safety is calculated using the following equation:

$$Fs = \frac{i_{cr}}{i_{exit}} \geq 3$$

Where:

i_{cr} is the critical exit gradient and ≅ 1,

i_{exit} is the real exit gradient at the downstream side of the structure.

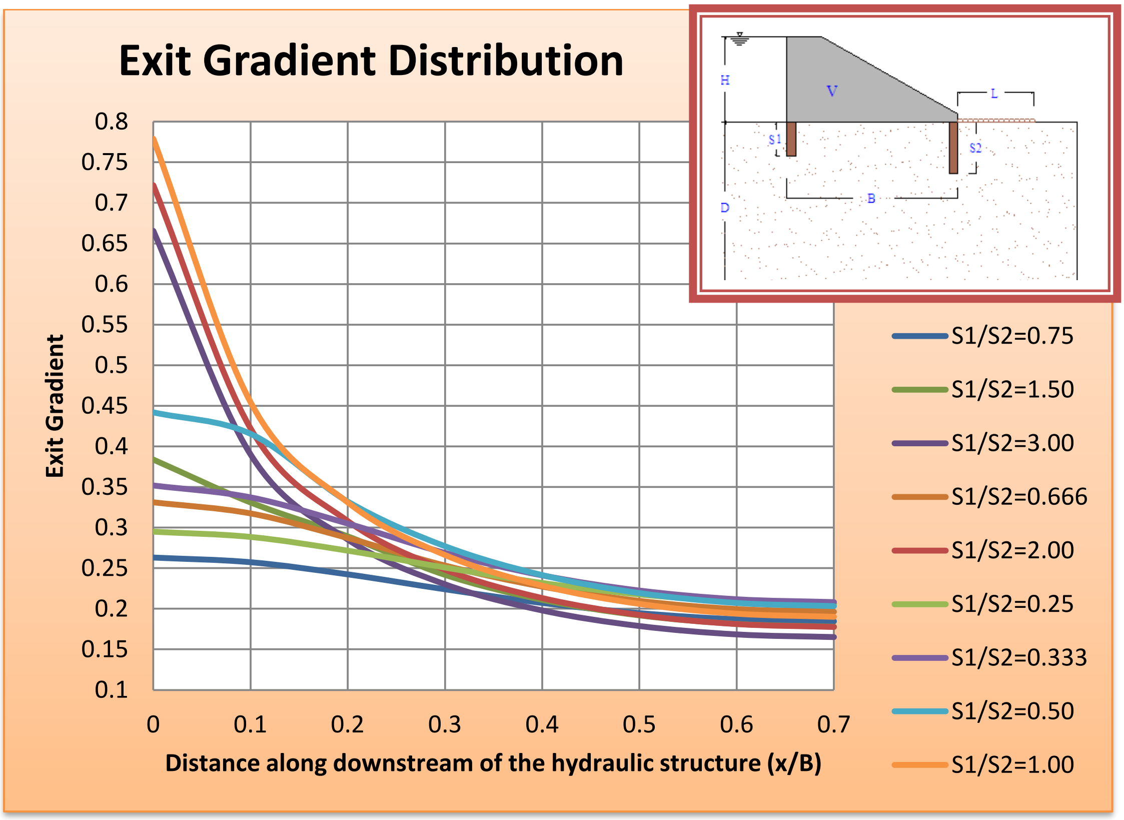

Fig (9) Exit Gradient Distribution under Hydraulic Structure with Different Depth of Upstream and Downstream Cutoffs for H= 5m and D=10m.

Figure (9) shows the variation of exit gradient with a non-dimensional distance along the downstream of the structure (X/B), for H=5 m and D=10 m with different values of the ratio of (S_1/S_2). This figure indicates the maximum exit gradient near the toe of the structure is given when S1/S2 = 1 followed by S1/S2 =2 and 3 respectively. For the other ratios of S1/S2 high reduction in the exit gradient value was observed near the toe of the structure. Beyond a distance of (x/B = 0.3) the values of exit gradient has similar variation with a narrow bundle curves. The curves indicate also that the highest length of protection required is at x/B = 0.25 approximately.

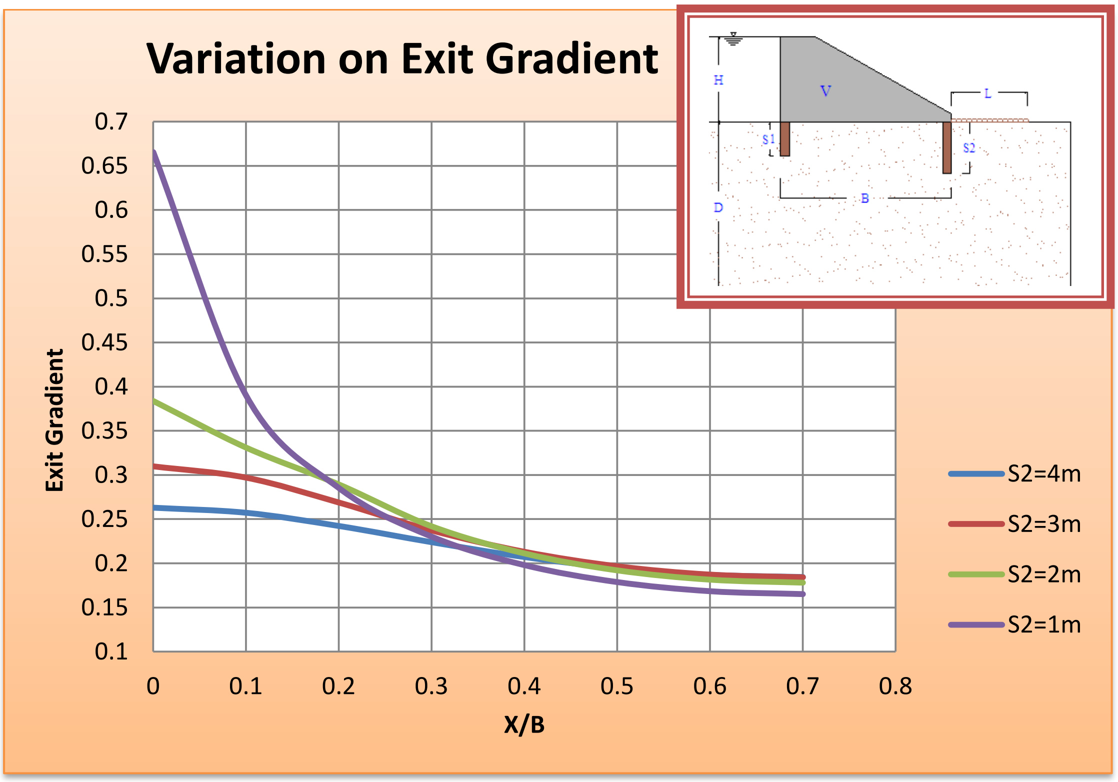

Fig (10) Variation of Exit Gradient for Hydraulic Structure with Downstream Cutoffs for S1=3ms.

In order to investigate the variation of exit gradient with fixed value of the length of upstream cutoff (S1) and different values of the length of the downstream cutoffs, figures 9,10 and 11 show this variation for S1 = 3,2 and 1m, respectively, with different values of S2 = 1,2,3 and 4m.

These figures indicate that the maximum exit gradient near the toe of the structure, occurs when (S2=1m) and considerable reduction resulted with the increase of the value of (S2). The effect of (S2) values is demolished for (x/B) $\geq$ 0.3.

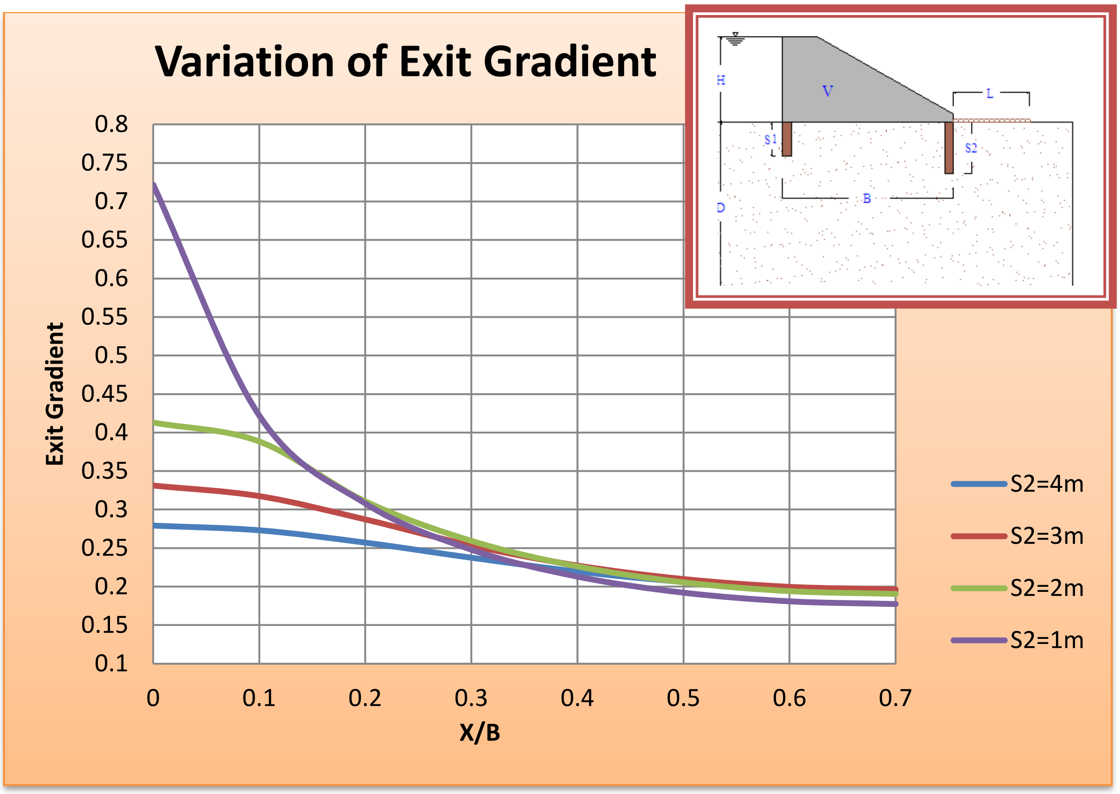

Fig (11) Variation of Exit Gradient for hydraulic structure with downstream cutoffs for S1=2ms.

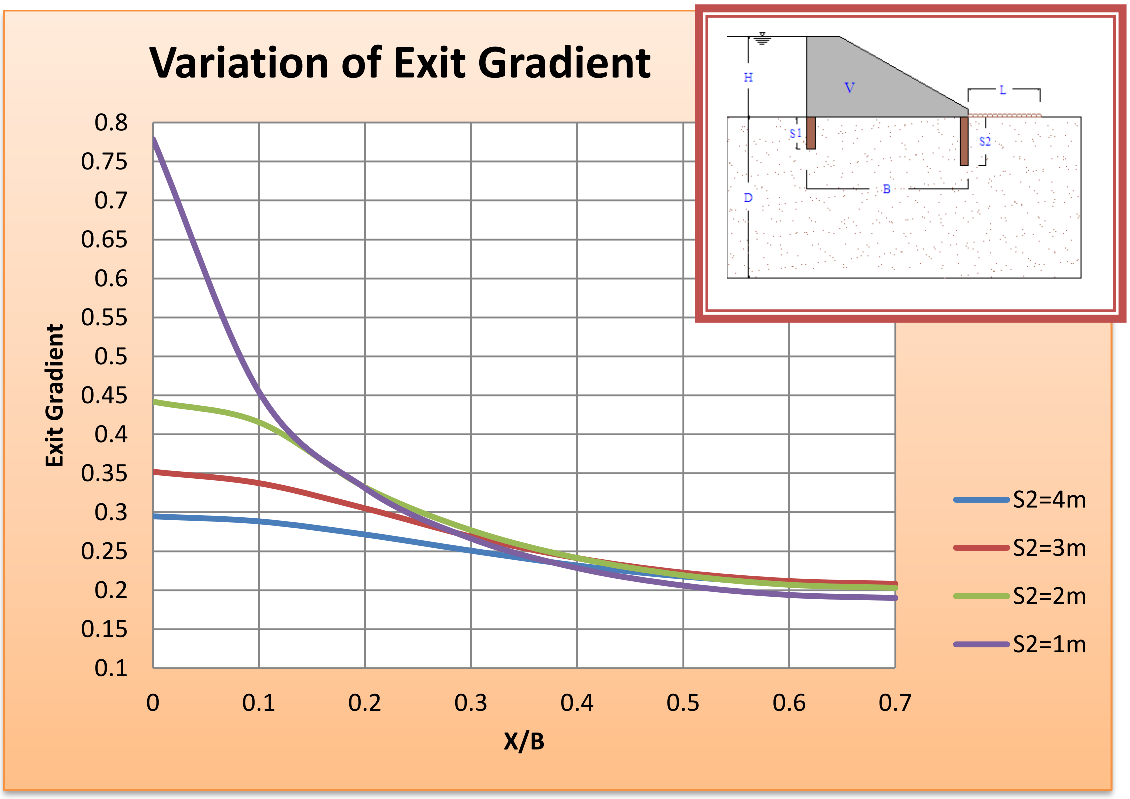

Fig (12) Variation of Exit Gradient for hydraulic structure with downstream cutoffs for S1=1ms.

Variation of Uplift Pressure under the Structure Foundation:

The uplift pressure variation along the structure foundation is important for deciding the volume of the superstructure required to provide a minimum factor of safety against uplift pressure failure of (2). This factor of safety is calculated according to the following equation:

$$Fs_{\text{uplift}} = \frac{\gamma V}{uplift\ force} \geq 2$$

Where:

Fs_{uplift} is the factor of safety against uplift pressure,

V: volume of concrete of the superstructure,

γ: Concrete weight density,

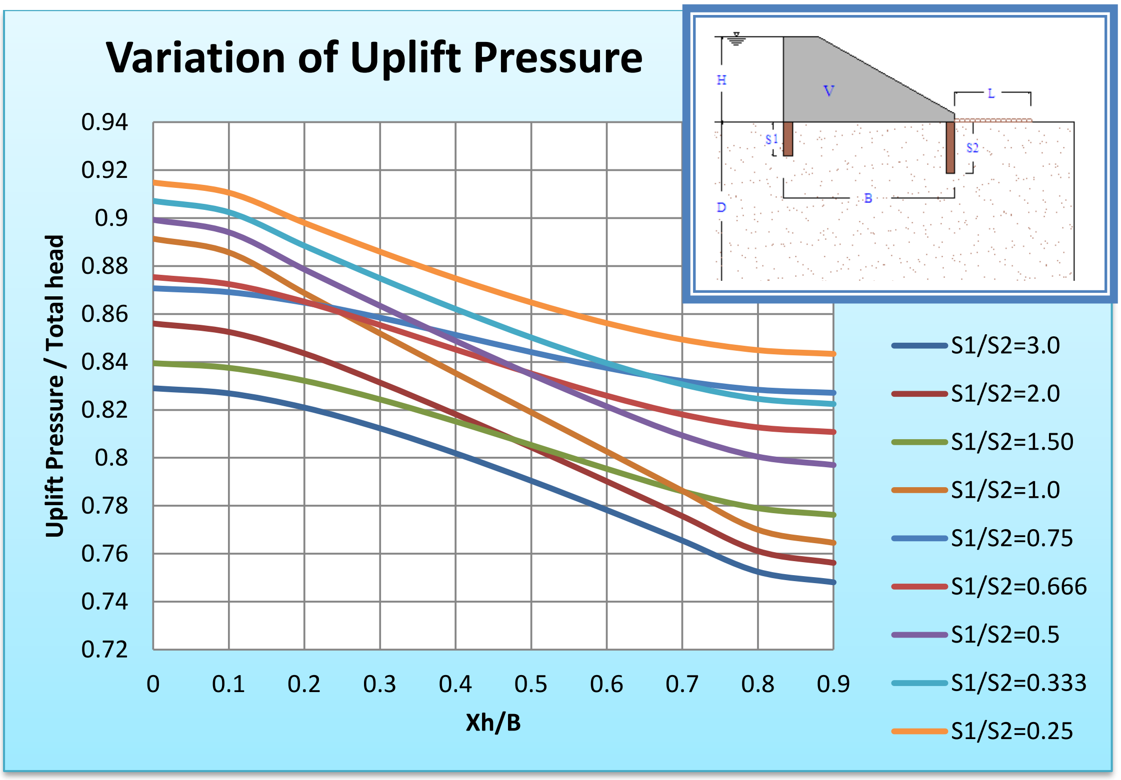

Fig (13) Variation of Uplift Head under a Hydraulic Structure Using Geo-Studio Model

Figure (13) shows the variations of the ratio of the uplift pressure over total head as ordinate with the distance from the heel of the structure over the length of the floor (x/B) as abscissa for different values of the ratio of (S1/S2).

Figure (13) indicates that all the pressure values were enveloped by two limiting curves, the upper one is the curve of the minimum selected (S1/S2 = 0.25) and the lower curve of the maximum selected (S1/S2 = 3.0). The other (S1/S2) ratios were falling between these two envelope curves.

The variation on the values of the ordinate dose not exhibit parallel behavior, but with some intersections. The maximum pressure to total head occur at the heel is approximately (0.918), while the minimum ratio occur at the end of the floor of approximately (0.75).

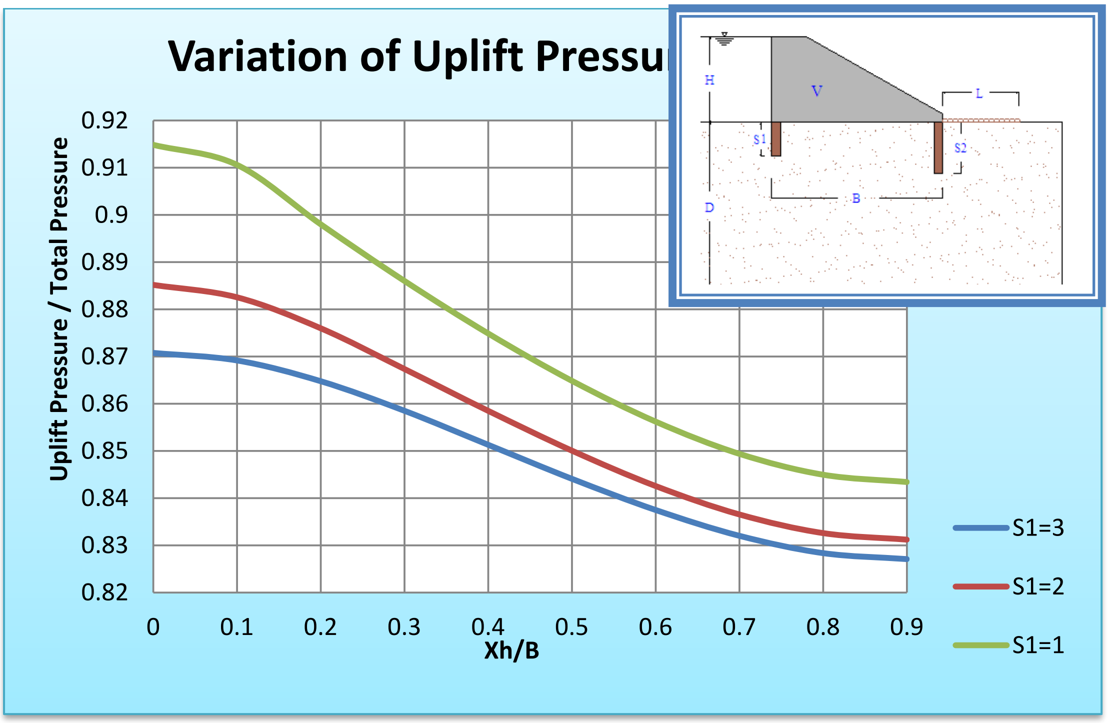

Fig (14) Variation of Uplift Pressure under a Hydraulic Structure Using Geo-Studio Results for S2=4m.

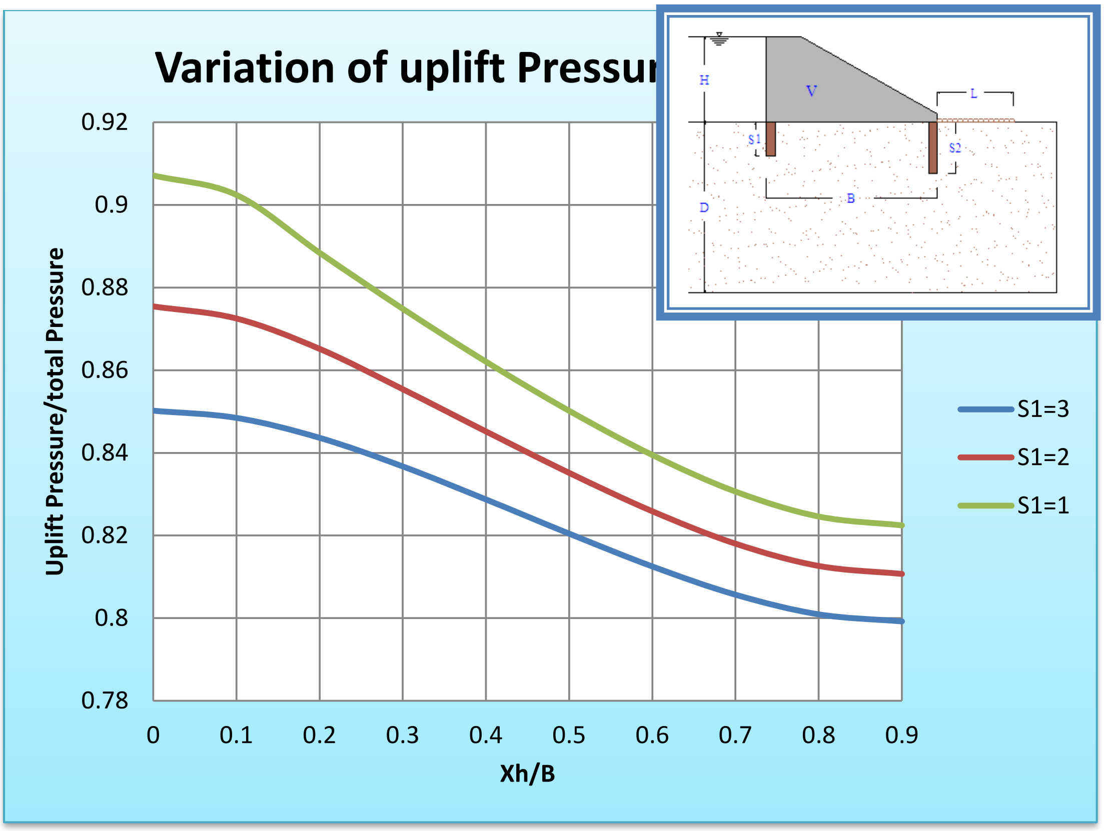

Fig (15) Variation of Uplift Pressure under a Hydraulic Structure Using Geo-Studio Results for S2=3m

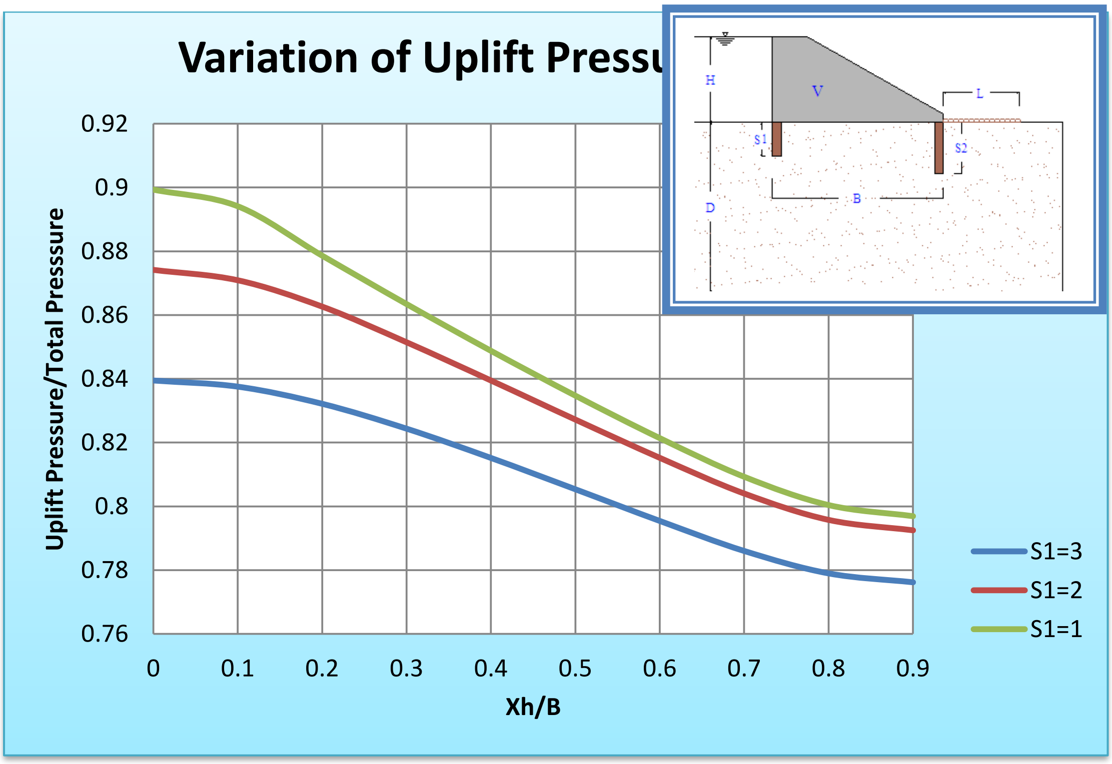

Fig (16) Variation of Uplift Pressure under a Hydraulic Structure Using Geo-Studio Results for S2=2m

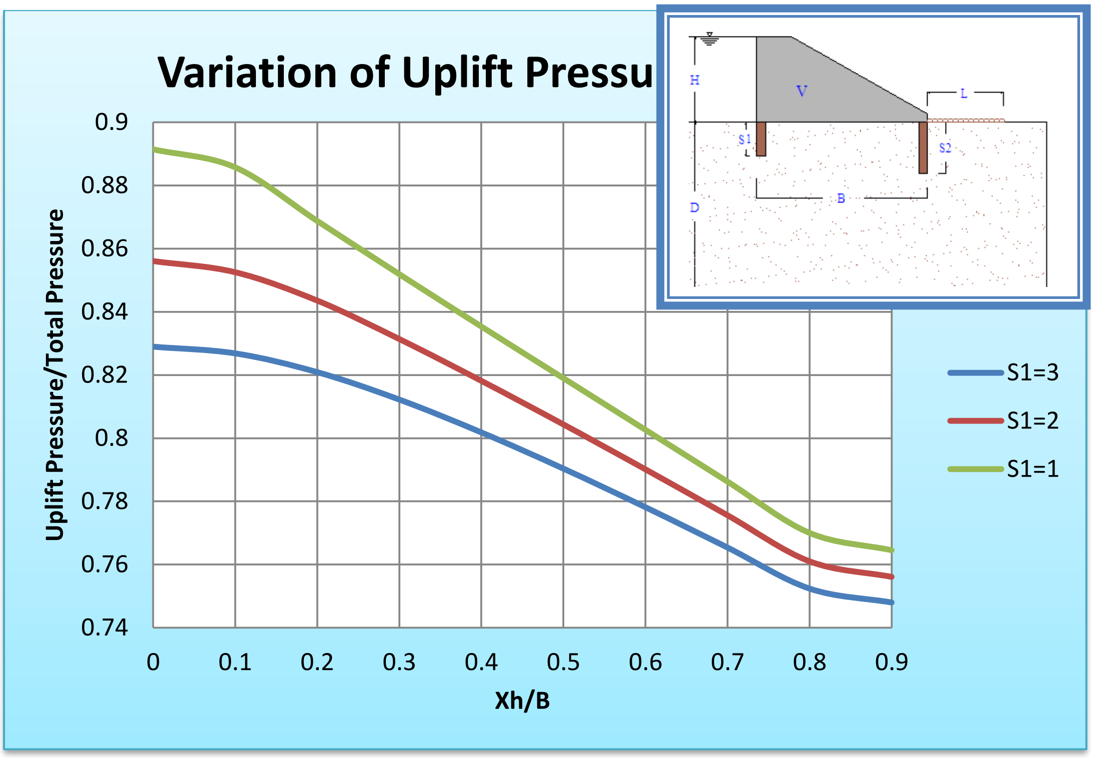

Fig (17) Variation of Uplift Pressure under a Hydraulic Structure Using Geo-Studio Results for S2=1m.

In order to investigate the uplift pressure distribution with fixed value of the length of the downstream cutoff and different values of the length of the upstream cutoffs, figures (14, 15, 16 and 17) were presented for (S2 = 4, 3, 2 and 1) respectively. Each of these figures shows three curves for (S1 = 1, 2 and 3). These figures indicate that the value of S1 had considerable effect on decreasing the uplift pressure, especially when increasing the value of S1 from (1 to 2). Moreover, the curves indicate parallel behaviors with no intersection.

Conclusions:

1) The maximum exit gradient near the toe of the structure is observed when the ratio of the length of upstream cutoff to the length of downstream cutoff (S1/S2 = 1). This maximum value of the exit gradient will decrease as the ratio of (S1/S2) increased.
2) The exit gradient exhibits little variation with the ratio of (S1/S2) beyond a distance of (x/B = 0.3) from the toe of the structure. Moreover, the slope of variation decreases with the increase of x/B.
3) The analysis indicate that the highest length of protection required at the downstream side as at (x/B = 0.25).
4) The effect of length of the downstream cutoff (S2) on the exit gradient is demolished beyond a distance of (x/B = 0.3).
5) The analysis of the variation of the uplift pressure indicate that all the pressure values were enveloped by two limit in curves, the upper one is the one of the minimum selected (S1/S2) ratio of (0.25) and the lower curve is for the maximum (S1/S2) ratio of (0.3). The value of the pressure for the other (S1/S2) ratios was falling between these two envelope curves.
6) The maximum pressure to total head ratio, occurs at the heel of the structure is approximately (0.918), while the minimum ratio occurs at the end of the floor which is approximately (0.75).
7) The analysis indicates that the value of upstream cutoffs has considerable effect on decreasing the uplift pressure, especially from a value of (1m to 2m).

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