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1 INTRODUCTION

1.1 SUMMARY OF THE THESIS

The topic of the thesis is "Numerical Modeling of Location Optimization of Drainage Gallery in Gravity Dams". An effort has been made here to find out the optimum location of the drainage gallery inside concrete gravity dams using Finite Element Modeling (FEM) analysis of a model. Gravity dams depend upon its own weight for resisting the uplift pressure which is exerted by the seepage of the water from the foundation of the dam. The effect of hydraulic uplift pressure can be reduced by using a drainage gallery inside the gravity dams, and hence the weight of the dam can be reduced for achieving the same factor of safety. The position of the drainage gallery affects the hydraulic uplift force acting on the foundation of the dam. Hence the optimum position of the drainage gallery under gravity dam is found out which results in the maximum reduction factor of hydraulic uplift force acting on the base of the dam. Also the increase in factor of safety of the gravity dam is worked out after proving drainage gallery in the gravity dam.

An isotropic and homogeneous two dimensional model is prepared and analyzed from Rocscience Phase 2 v 8.0. Based on the pore pressure obtained from the software, hydraulic uplift force for different upstream water level conditions are calculated manually. The results of numerical model are compared for different water head available at the upstream of the dam and for different positions of the drainage gallery provided inside the dam. Finally, the effect of the drainage gallery on the factor of safety of the dam is analyzed.

1.2 BACKGROUND

Concrete dams suffer permanently the action of forces. Some of these forces tend to destabilize the dam like the thrust of the upstream reservoir and the uplift pressures under its base. To counterbalance these forces there is the weight of the structure and the thrust of the downstream reservoir. The correlation between these forces is given by the expression:

$$F_s = \frac{(P - U)tan\phi + cA}{H_u - H_d}$$

where F_s is the safety against sliding, P is the weight of the structure (kN), H_u is the force due to the upstream reservoir (kN), H_d is the force due to downstream reservoir (kN), U is the uplift force (kN), ϕ is the friction angle along the base (^{o}), c is the cohesion along the base (kN/m^2) and A is the area of the base (m^2).

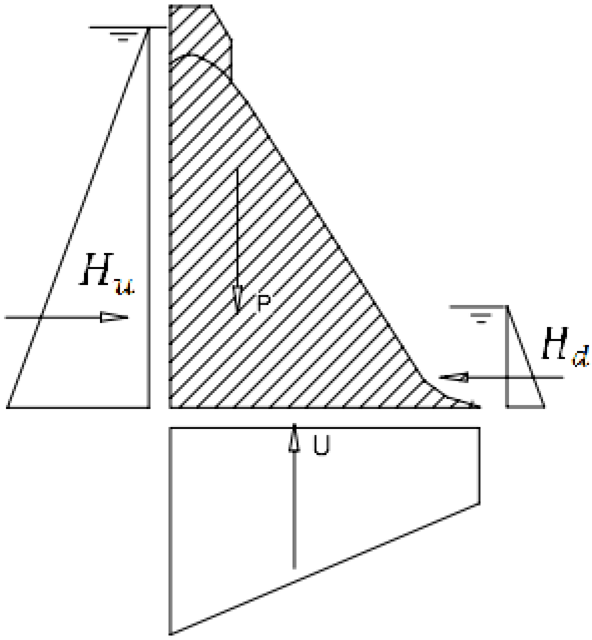

Figure 1-1: Forces acting on a Concrete Dam

As the friction angle and the cohesion are properties of the foundation materials, there are only two forces in equation for factor of safety (F_s) that can be altered by designers and they are the weight of the structure (P) and the uplift force (U). The factor of safety (F_s) is constant when the difference between weight and uplift (P-U) is also constant. This means that for a required factor of safety, a small uplift force requires a small weight for the structure, in order to maintain stability. As the weight of the structure can be altered through changes in its geometry, a method that would permit the design of an adequate subsurface drainage system to reduce the uplift pressures would lead to reductions in concrete dam costs.

1.3 THE NEED FOR RESEARCH

The provision of the drainage gallery in the dam significantly reduces the uplift pressure. The reduction in the uplift pressure depends upon the position of the drainage gallery. The provision of the drainage gallery further downstream of the dam increases the uplift pressure on the upstream portion of the dam from drainage gallery, whereas decreases the uplift pressure on the downstream portion of the dam. So there is a need of research to be taken for finding the optimum position of the drainage gallery in the dam, to ensure the maximum stability for a given weight of a dam. In this thesis, an attempt is made for finding the optimum position of the drainage gallery in the dam which gives the maximum stability. In the design phase of the projects, the optimum position of the drainage gallery also leads to the economic design of the dam for specified factor of safety.

1.4 OBJECTIVES OF THE STUDY

1.4.1 Global Objective

The main aim of carrying this research work is to find out the optimum position of the drainage gallery inside the dam for minimum hydraulic uplift force. This optimum position of drainage gallery is results in the reduced weight of the dam for a given factor of safety, and hence results in economic design of the dams.

1.4.2 Specific Objective

- To find the variation of the hydraulic uplift force with respect to the water head available at the upstream of the dam
- To find the variation of the hydraulic uplift force with respect to the placement of the drainage gallery inside the body of the dam
- To find out the optimum distance of the drainage gallery from upstream face of the dam
- To compare the reduction factor(RF) of the hydraulic uplift force for the various options of drainage gallery
- To compare the effect of various positions of drainage gallery on the stability of dam
- To study the effect of downstream water on the uplift force
- To find the discharge occurring into a single drain hole
- To study the effect of the height of the drainage gallery
- To study the effect of size and depth of the drain holes

1.5 LIMITATIONS OF THE STUDY

The limitations of the study carried out are:

- The study is carried out for two dimensional models which may not incorporate the three dimensional drainage behavior of the gallery.
- The permeability of the rockmass is considered isotropic, but it actually shows directional behavior, which cannot be captured in the proposed model.
- The rock foundation is considered isotropic and homogeneous, without any fracturing.
- The effect of grouting in the rock foundation is ignored.
- The drainage holes from drainage gallery are just extended to touch the rock foundation, without penetrating the rock.
- The effect of filling of the drain holes are ignored i.e. the pressure inside the drain holes is assumed atmospheric at any time.
- No tensile crack is developed in the concrete dam heel and the drainage gallery is functioning properly without choking of the drain holes.
- The concrete dam is completely impervious and no water flows though the dam.
- The rock foundation is assumed as the horizontal river bed.
- The dam axis is assumed perpendicular to the flow direction of the river.
- The quantity of water drained by the circular drain holes is same as that drained by the rectangular hole of same cross-sectional area (assumed for calculating the spacing of drain holes).
- The water inside the drainage trench (in the plane strain formulation) is drained by the circular drain holes (assumed for calculating the spacing of drain holes).
- The discharge velocity in the cross-section of drain holes is constant, which is equal to the discharge velocity at the center of the drain holes (assumed for calculating the discharge of drain holes).
- The entry of water into the drainage gallery is only assumed through the drain holes.

1.6 ORGANIZATION OF THE STUDY

This report is organized into five chapters as:

Chapter I deal with introduction, summary of the study, objectives of the study, and limitation of the study.

Chapter II describes the theories, which is related with the study. It contains relevant information and data available in past research, papers, journals etc.

Chapter III describes the methodology adopted for this research.

Chapter IV includes the data observed from numerical models and their analysis and presentation as results and discussions.

Chapter V includes conclusions and recommendations regarding the whole study so that it will help for further research and study of the same nature.

The appendices contain some graphs, tables and outputs. It also contains different data used in the research works.

2 LITERATURE REVIEW

2.1 INTRODUCTION

By definition, a gravity dam is a structure which is designed in such a way that its own weight resists the external forces. Such a dam may be constructed of masonry or concrete. The various external forces acting on a gravity dam are water pressure, uplift pressure, pressure due to earthquake forces, silt pressure, wave pressure and ice pressure. The stabilizing force is the weight of the dam itself. So, on reducing the external forces, the weight of the gravity dam is also reduced for the same factor of safety.

So for economic design of the gravity dam, the external forces on the dam should be reduced as far as possible. After water pressure, uplift pressure is the second major external force and must be accounted for in all calculations. Water seepage through the pores, cracks and fissures of the foundation material, and water seepage through the dam body and then to the bottom through the joints between the body of the dam and its foundation at the base, exert an uplift pressure on the base of the dam.

Besides collecting water from various drain holes, drainage gallery also provides access for inspection purposes to monitor the behavior of the dam, and to carry out remedial work if required. The provision of drainage gallery in the dam significantly reduces the uplift pressure. Foundation gallery, for the purpose of drainage and foundation grouting, should be provided in the body of the dam where height of the dam above normal foundation level is more than 10m (measured up to the crest level in case of overflow portion of the dam). For lesser heads, its necessity should be left to the discretion of the designer (IS 12966(Part 1):1992, Code of Practice for Galleries and Other Openings in Dams).

The uplift pressure acting on the base of the dam is greatly influenced by the presence of drainage gallery. On shifting the position of the drainage gallery towards downstream face of the dam, the uplift pressure on the upstream portion of the dam is increased whereas the uplift pressure on the downstream portion of the dam is decreased. Hence the uplift force acting on the base of the dam is changed on changing the position of the drainage gallery. Hence, an optimum distance of drainage gallery from upstream face of the dam should be found out, for the minimum uplift force.

2.2 GALLERY IN DAMS

The gallery is an opening within dam which provides access into or through the dam [IS 12966(Part1):1992: Code of Practice for Galleries and Other Openings in Dams: General Requirements].

2.2.1 Purpose of Gallery:

The need for galleries varies from dam to dam. Some of the common purposes for which galleries are provided are as follows:

- To provide drainage way for water seeping through the upstream face of the dam and from the foundations;
- To provide space for drilling holes and grouting the foundation in order to provide a grout curtain;
- To provide access to the interior of the dam for observing its behavior after completion;
- To provide access to chambers like hoist chamber, pump chamber, pump well and instrument niches, etc;
- Visitor's gallery to provide access routes for visitors.

2.2.2 Foundation Gallery

It is a gallery which generally extends over the length of the dam near the rock profile conforming in elevation to the transverse profile of the canyon; in plan, it is near and parallel to the axis of the dam. From this gallery, holes are drilled and grouted for the main grout curtain and drainage holes are drilled for draining water seeping through the foundation in order to provide relief in uplift pressures.

2.3 METHODS OF DRAINAGE IN GRAVITY DAMS:

In reference to the IS: 10135-1985 (Code of Practice for Drainage System for Gravity Dams, their Foundations and Abutments, First Revision), the following methods of drainage of dams are suggested:

2.3.1 Surface Drainage:

All open surfaces in the vicinity of the dam shall be provided with adequate drainage. For this purpose open surface channels shall be so designed and laid as to drain off the area effectively and carry away the surface run-off into the reservoir upstream of the dam or into the river downstream of the dam. The service roads and other approach roads leading to dam shall have proper camber and longitudinal slopes for catch water drains. The water from these catch drains shall be collected at suitable intervals depending on topography, rainfall, etc, and led away into the natural drains away from the dam. The roadway, the ducts for electric cable, the crane rail recesses and any other recesses provided at the top of the dam shall be drained through pipes of at least 100 mm diameter.

2.3.2 Sub-surface Drainage

This shall be provided for the following purposes, if necessary:

a) Protection of slopes:

b) Drainage of abutments:

Protection of Slopes

In some river valley projects, the hill slopes in the vicinity of abutments need to be protected against likely slips. This shall be done by either providing a combination of concrete cladding/shotcreting and drainage holes or any other suitable arrangement or by providing drainage holes only. Provision of non-return valves, which allow water to flow towards the reservoir area or hill slopes in the vicinity of abutment only, shall be made in the drainage holes.

Drainage of Abutments

The drainage gallery may be extended into the abutment rock, together with provision of cross tunnels, as drainage tunnels, if necessary, for ensuring the stability of abutment blocks or the abutment.

2.3.3 Internal Drainage of Dam

Internal drainage of a gravity dam usually comprises porous concrete drains/formed drains at the contraction joints and in the body of the dam.

- Vertical drains at contraction joints shall be provided to intercept the seepage water through the joint and such seepage water shall ultimately be let out into the drainage gallery system.
- The internal drainage of concrete/masonry dam shall be provided with 200 mm diameter vertical drains or uniformly inclined (till they meet the gallery) at 3 m centre to centre. For masonry dams these shall be of precast porous concrete while for concrete dams these shall be formed drains. These shall convey the seepage water through the body of the masonry/concrete dam to drainage gallery system. Suitable water seal to prevent entry of air may be provided at the discharge end of the drainage pipe in the gallery. For masonry dams, the drains shall be of porous concrete blocks while for concrete dams, they shall be formed drains.

2.3.4 Foundation Drainage Gallery

The main aim of a foundation drainage gallery is to collect seepage water from foundation and the body of the dam. Besides, it provides space for drilling and grouting the foundations and inspection of dam structure.

- The upstream face of the gallery shall be located at a minimum distance of 5 percent of the maximum reservoir head or 3 m from the upstream face, whichever is more. A supplementary drainage gallery is sometimes provided towards the toe. For layout and size of gallery, reference may be made to ‘Indian Standard Code of practice for galleries and other openings in dams: Part 1 General requirements’.
- Various galleries in the dam and tunnels in the abutments receive water from drainage holes, joint drains, formed drains/porous concrete drains, seepage, grouting operations, washing and cleaning, fire- fighting, spring leaks, etc. This water should be drained away under gravity with a slope not flatter than 1 in 1000. The water collected in the galleries/tunnels below the general downstream level shall be led into one or two sumps provided and pumped out.
- Gallery shall invariably be provided in the body of the dam where height of the structure above normal foundation level is more than 10 m (measured up

to crest level in the case of overflow portion of the dam). For dams with heights below 10 m, the designer should consider the provision of gallery keeping in view factors like foundation condition and height of water retained.

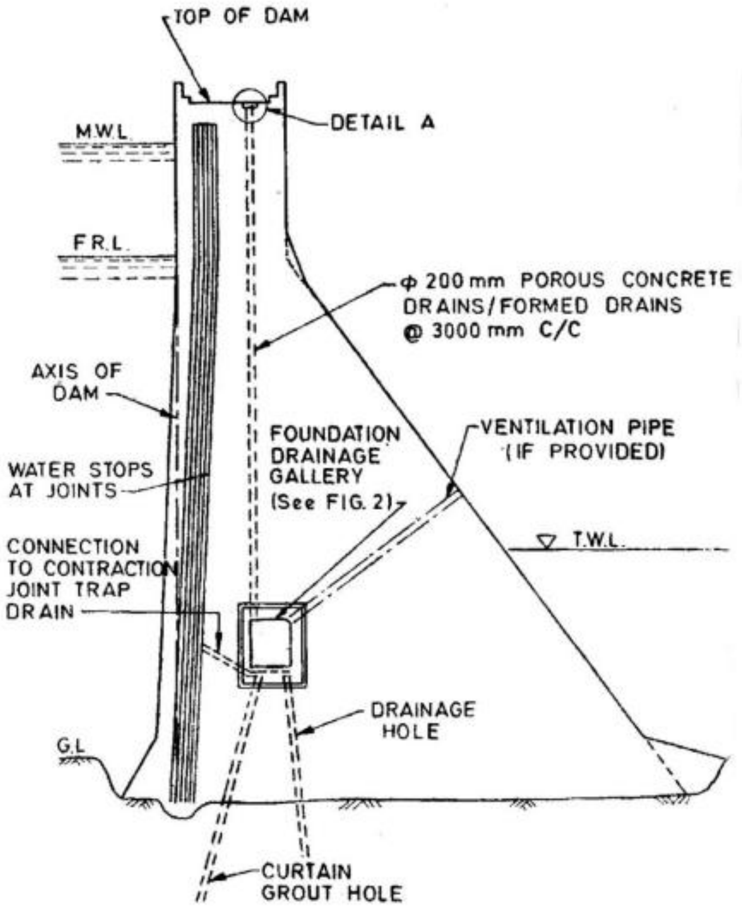

Figure 2-1: Dam section showing drainage gallery and other details [IS: 10135-1985]

2.3.5 Foundation Drainage

Foundation drainage provides a means to relieve the uplift under the dam foundations. This drainage is accomplished by a line of holes drilled from the foundation gallery into the foundation rock. The size, spacing and depth of these holes are assumed on the basis of physical characteristics of the foundation rock, foundation condition and depth of storage of the reservoir. The diameter of the hole is generally NX drill which is 75 mm. The spacing of the hole may be kept as 6 m centre to centre. The depth of the holes may be kept between 20 and 40 percent of the maximum reservoir depth and between 30 and 75 percent of the curtain grouting depth for preliminary design. The actual spacing and depth may be determined on the basis of geological conditions.

These should be further reviewed and holes provided at closer intervals or further deepened on the basis of actual observations after the reservoir is filled. To facilitate this, additional nipples/pipes shall be embedded in the gallery concrete. The drainage holes of 75 mm diameter are drilled through 100 mm diameter pipe embedded in the masonry/concrete portion. When drainage holes are drilled through soft foundations for the drainage of shear zones, faults, etc, a perforated pipe should be placed in the drainage holes and the space between walls of hole and this pipe should be filled with pea gravel. This arrangement would avoid caving-in of walls and the holes could be got washed, if required.

- Drainage holes should be drilled after all foundation grouting has been completed within a minimum horizontal distance of 15 m. The drainage holes shall be drilled, through the drainage, gallery, through previously installed metal pipe extending down to the foundation rock. Additional drainage holes or curtain grouting shall be provided, if uplift pressures higher than designed values are observed. After drilling, the pipes shall be plugged at top and seepage water from the hole shall be taken off at a T-joint and let to the gutter of gallery.
- Besides the foundation drainage gallery, the drainage holes shall be drilled through tunnels in the foundation and abutments, Spacing and depth of the holes shall depend on the geology.
- Where cross galleries, additional foundation galleries and drifts are introduced, necessary drainage arrangements should also be considered and provided.
- The seepage water from drainage holes should be monitored from consideration of quantity, contents of fines and chemicals and remedial action taken, if warranted.

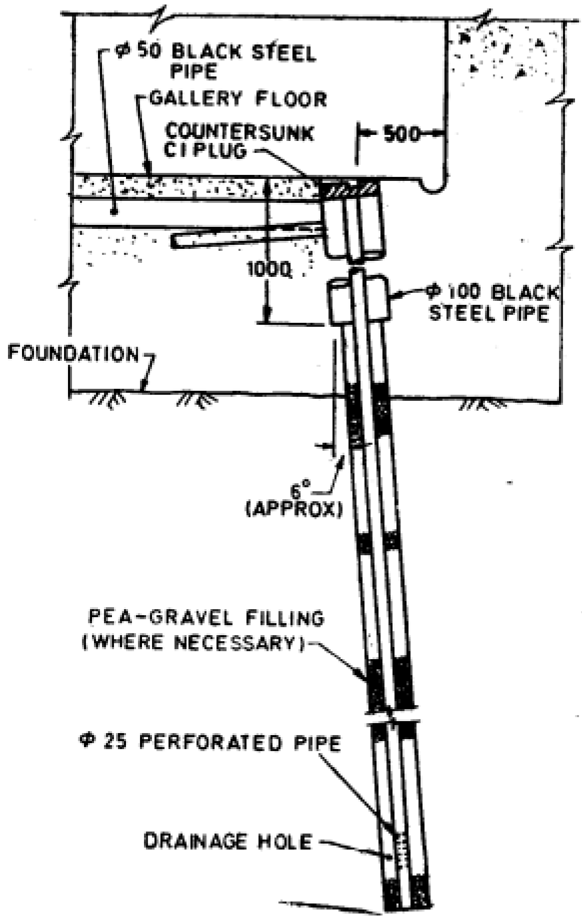

Figure 2-2: Foundation drainage pipe (All dimensions in mm) [IS: 10135-1985]

2.4 PREVIOUS STUDIES

Applying optimization techniques for determining 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. Davis (1969) proposed certain design criteria for the upward pressures caused by seepage under the foundations of gravity dams. Karim et al (1987-1988) 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.

United States Bureau of Reclamation (USBR) suggests the adoption of uplift pressure intensities equal to the hydrostatic pressure of water at the toe and heel joined by a straight line in between. When drainage galleries are provided in the body of the dam, which releases the uplift pressure built up under it, the magnitude of the uplift pressure recommended at the face of the gallery is equal to the hydrostatic pressure at the toe plus $1/3^{rd}$ the difference of the hydrostatic pressure at the heel and toe.

Raymond et al (1994) showed that uplift can be modeled in several ways in 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. El-Razek (1995) used a sand model to study case of lining subjected to high uplift pressure, based on minimum uplift force acting on the lining. He also investigated optimum numbers and locations of relief valves. El-Razek et al (2001) determined experimentally the optimum location of the drainage gallery underneath gravity dam. Da Silva (2005) investigated the influence of the dimensions, coarseness and inclination of drains on the upward pressures, numbers and locations of the drainage gallery, for a dam on homogeneous and isotropic material. Al-Delewy et. al. (2006) 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.

2.5 THE SAND MODEL EXPERIMENT

El-Razek el at (2001) determined the optimum location of the vertical drainage gallery beneath floor of the gravity dam. The experimental setup consists of one box divided into three tanks, the first is used to control head upstream the dam model, the second which locates in the middle includes the dam model which rests on a sandy soil, and the third one is used to control the downstream head. The partitions between all tanks are perforated and covered with synthetic material to allow only movement of water from upstream to downstream without sand particles. The experiments are performed in the laboratory of Department of Irrigation and Hydraulics, Faculty of Engineering, Alexandria University.

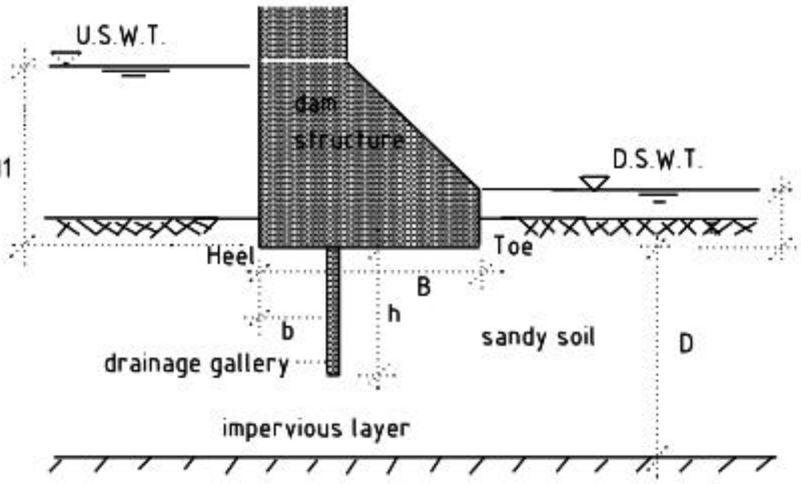

Figure 2-3: Cross-section of the case studied [El-Razek et al(2001)]

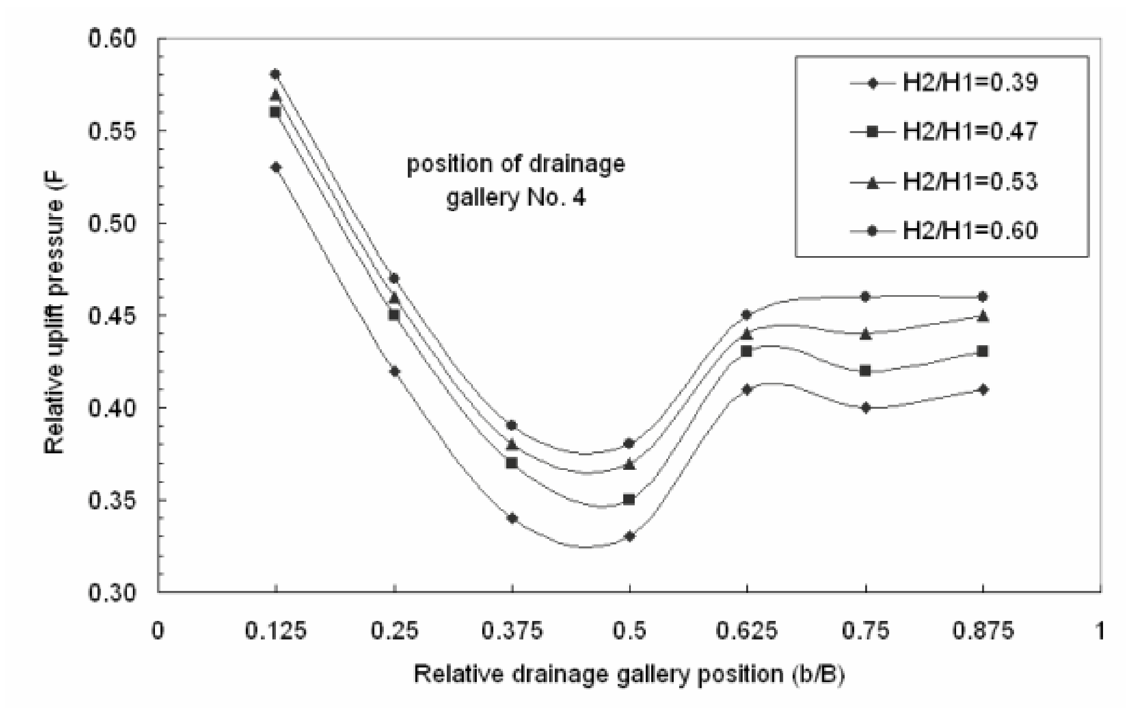

Figure 2-4: Relative uplift pressure (P/H) versus relative drainage gallery position (b/B) at different values of H_2 /H_1 [El-Razek et al (2001)]

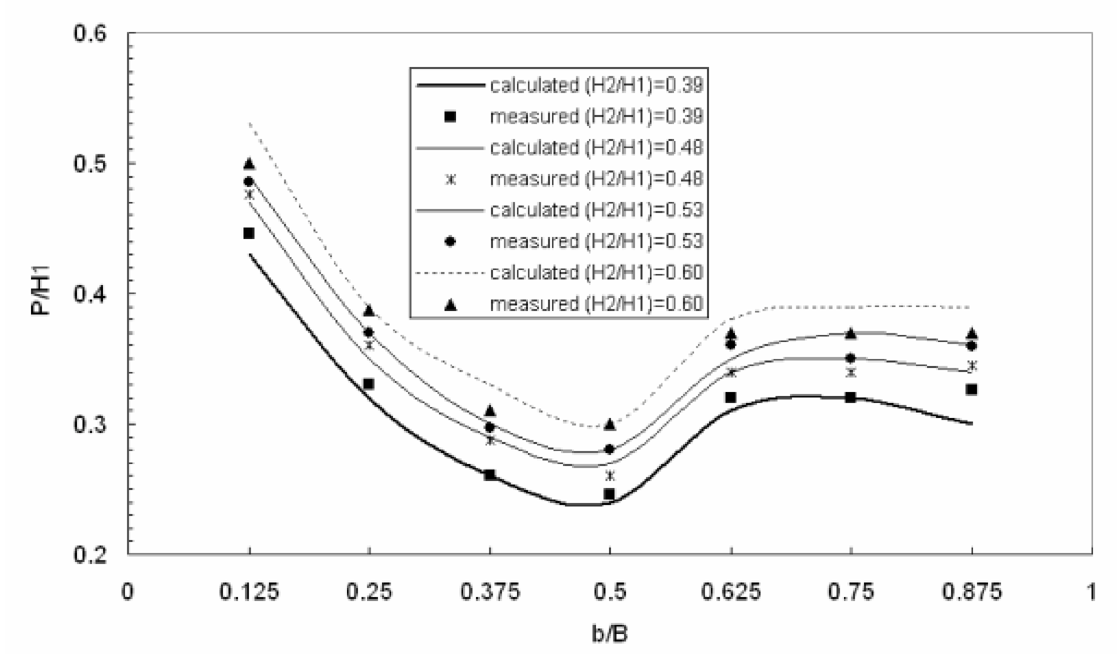

Figure 2-5: The calculated and measured relative uplift pressures (P/H_1) versus relative position of the drainage gallery (b/B) for H_2/H_1= 0.39, 0.48, 0.53 and 0.6 [El-Razek et al(2001)]

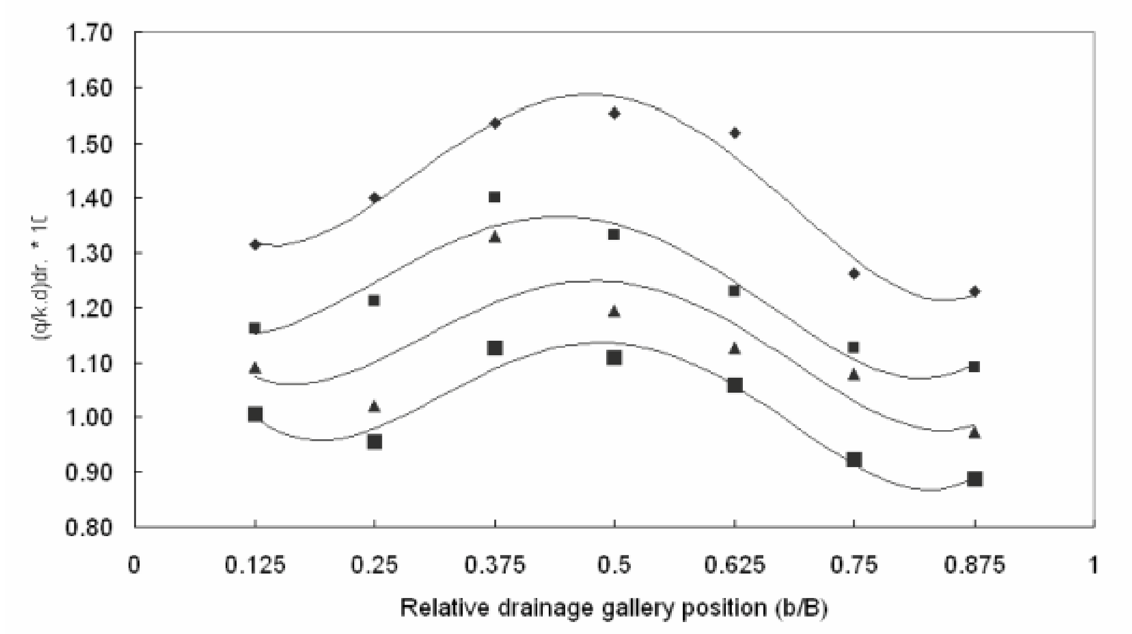

Figure 2-6: Relative seepage discharge entering drainage gallery (q/k.d) dr. versus its relative position (b/B) [El-Razek et al (2001)]

From the sand model experiment, the optimum position of the drainage gallery, constructed beneath gravity dam, was found at the midpoint of the base of the dam (

i.e. b/B = 0.5) at which reduction in volume of the uplift pressures is maximum and equals about 0.54. The optimum position of the drainage gallery was said to be achieved at b/B = 0.5, at which seepage discharge entering the drainage gallery is maximum.

2.6 FEM MODELING OF DRAINAGE GALLERY UNDER GRAVITY DAM

Uday et al(2016) used numerical method (two dimensional finite element) to analyze the 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 were prepared, one 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 indicated that the gallery drain nearest the upstream side close to Xd/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 numerical analysis was carried out on computer program package “SLIDE V.5.005”.

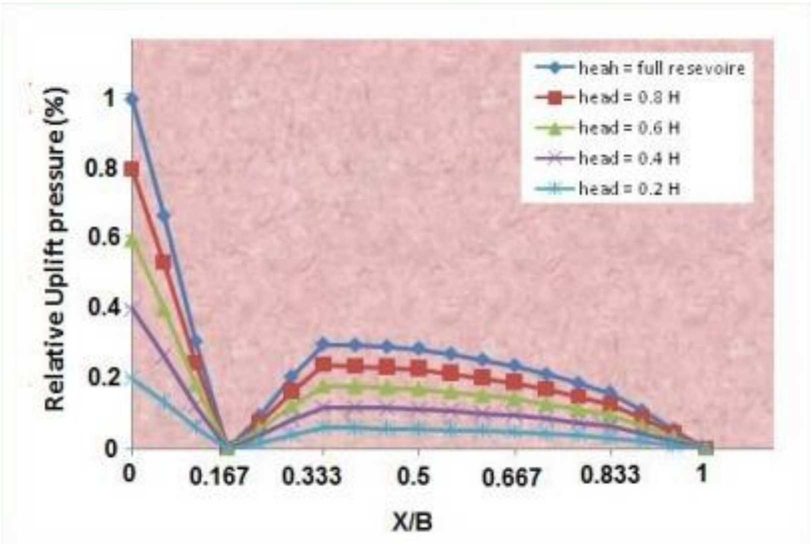

Figure 2-7: Uplift pressure under the base of gravity dam with drain for different reservoir at X/B=0.167 [Uday et al (2016)]

The optimum position of the drainage gallery was achieved at X/B=0.167, from the numerical model.

2.7 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].

2.8 GOVERNING EQUATIONS:

2.8.1 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)].

$$U = -kx\frac{\delta H}{\delta x}$$

$$V = -ky\frac{\delta H}{\delta y}$$

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

$$\frac{\delta U}{\delta x} + \frac{\delta V}{\delta y} = 0$$

Substituting Darcy's equation in continuity equation:

$$\frac{\delta}{\delta x}(-kx\frac{\delta H}{\delta x}) + \frac{\delta}{\delta y}(-ky\frac{\delta H}{\delta y}) = 0$$

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

Then above equation becomes:

$$\frac{\delta^2 H}{\delta x^2} + \frac{\delta^2 H}{\delta y^2} = 0$$

This 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. $k_x=k_y$

Then Laplace equation becomes:

$$k_x \frac{\delta^2 H}{\delta x^2} + k_y \frac{\delta^2 H}{\delta y^2} = 0$$

There is another benefit function for the flow through porous media, which is called stream function ψ(x,y).

$$U = \frac{\delta \psi}{\delta y}$$

$$V = \frac{\delta \psi}{\delta x}$$

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:

$$\frac{\delta V}{\delta y} - \frac{\delta U}{\delta y} = 0$$

Substituting in the above equation, we get:

$$\frac{\delta^2 \psi}{\delta x^2} + k_y \frac{\delta^2 \psi}{\delta y^2} = 0$$

This represents Laplace equation for stream function.

2.8.2 Seepage Equation for Homogeneous Isotropic Foundation:

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

$$\frac{\delta^2 h}{\delta x^2} + \frac{\delta^2 h}{\delta y^2} + \frac{\delta^2 h}{\delta z^2} = 0$$

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:

$$\frac{\delta^2 h}{\delta x^2} + \frac{\delta^2 h}{\delta y^2} = 0$$

2.9 NUMERICAL MODELING

Design and analysis problems in geotechnical engineering practices can be dealt with, by using any one of the three analytical methods viz; Physical models, Mathematical models and Numerical models.

Physical models are time consuming and costlier to be prepared and analyzed. The complexity in geometry, non-homogeneity, and non-linear constitutive behavior of the medium makes it difficult for mathematical model (closed form solution). Numerical modeling thus combined with the mathematical model in correct approximation of the material properties give solutions to more complex analysis and design solutions.

Numerical models are mathematical models that use some sort of numerical time-stepping procedure to obtain the models behavior over time. The mathematical solution is represented by a generated table and/or graph.

Number of numerical techniques is available for geotechnical engineering, they are Finite Element Method (FEM), Finite Difference Method (FDM), Boundary Element Method (BEM), Discrete Element Method (DEM), Spectral Element Method (SEM) etc.

The finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It is also referred to as finite element analysis (FEA). It subdivides a large problem into smaller, simpler parts that are called finite elements. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEM then uses variational methods from the calculus of variations to approximate a solution by minimizing an associated error function.

FEM analysis basically consists of three steps:

- Model Discritization,
- Loading and application of boundary condition,
- Output generation.

2.9.1 Phase^2 as FEM Tool

Phase2 is a two-dimensional elasto-plastic finite element program for calculating stresses and displacements around underground openings, and can be used to solve a wide range of mining, geotechnical and civil engineering problems.

It can be used for a wide range of engineering projects and includes excavation design, slope stability, groundwater seepage, probabilistic analysis, consolidation, and dynamic analysis capabilities.

Phase^2 includes steady-state, finite element groundwater seepage analysis built right into the program. So, there is no need to use a separate groundwater program. Pore pressure is determined as well as flow and gradient, based on user defined hydraulic boundary conditions and material conductivity. Pore pressure results are automatically incorporated into the stress analysis.

3 METHODOLOGY

3.1 METHODOLOGY

The formulation of the problem is described in the Appendix I. A methodology is proposed for achieving the research objectives. The flowchart of the proposed methodology is given in figure 3-1.

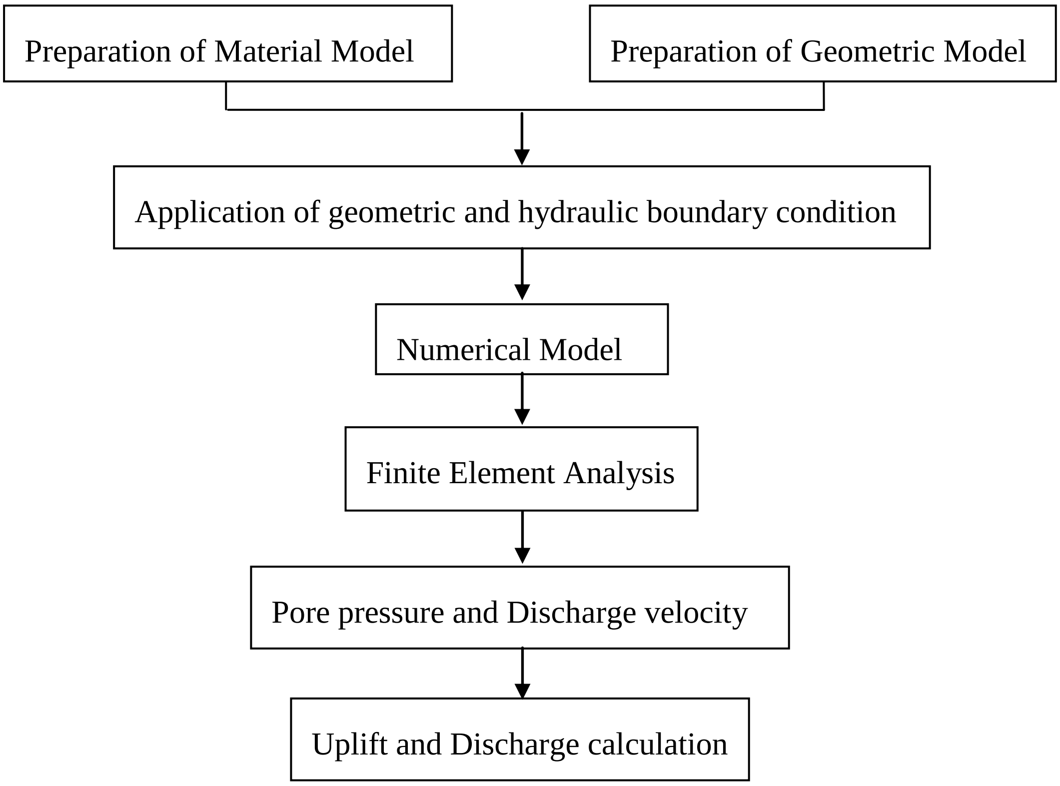

Figure 3-1: Flowchart for the proposed methodology

3.2 PREPARATION OF MATERIAL MODEL

The material model is prepared in Rocscience Phase2 version 8.0. The type of model is Mohr-Coulomb model which its default values. Since we are only performing groundwater analysis in the software, the strength criteria of the material model is independent of the result we obtain in the analysis.

The coefficient of permeability of the rock mass varies in a wide range depending upon the characteristics of the discontinuities present in the rockmass. Atkinson (2000) has presented hydraulic conductivity of various geological models. The range of hydraulic conductivity of fractured igneous and metamorphic rocks is 1e-1cm/sec to 1e-6cm/sec whereas the range of hydraulic conductivity of unfractured igneous and metamorphic rocks is 1e-8cm/sec to 1e-11cm/sec (Atkinson, 2000). With discussion with the supervisor, the coefficient of permeability of the foundation rock mass is assumed as 1e-7m/sec for unfractured rock.

3.3 PREPARATION OF GEOMETRICAL MODEL FOR ANALYSIS

The procedure consists of following steps:

Step1: Identification of problem domain

The size of model considered for the numerical analysis is 300m X 100m. The heel of the dam is considered as the origin. The maximum height of the water in reservoir is 100m. A freeboard of 10m is assumed. The height to width ratio of the dam is considered as 1:0.85. The model extends 100m upstream, 200m downstream and 100m depth from the heel of the dam. The width of the dam base is 93.5m.

Step2: Generation of Mesh

A uniform three-nodded triangle is used for the generation of the mesh for finite element formulation. A total of 10712 mesh elements were generated for the FEM formulation.

Step3: Boundary Condition

The geometric boundary condition applied to the model is restrained horizontal and vertical displacement along bottom boundary and restrained horizontal displacement along left and right boundary; whereas the top of the model is set free to simulate the condition of ground surface. Since only groundwater analysis is to be performed, the results of the analysis are independent of geometric boundary condition and only depends upon the hydraulic boundary condition. The hydraulic boundary condition applied to the model is the total head of water along upstream and downstream portion of the dam in the model, where as zero pressure boundary at the drain holes.

Step4: FEM Analysis

The finite element analysis is only done for the groundwater calculation. The pore pressure and discharge velocity were calculated at the nodes of the dam base at 100 equally spaced locations. The uplift force exerted by the pore pressure along the base of the dam is calculated manually from the pore pressure plot of the model. Similarly, the discharges were calculated manually from the discharge velocity plot of the model.

Step5: Comparison of different results

After obtaining the pore pressures and discharge velocities from different models, a comparison is done for the uplift force at dam base and discharge in the drain holes for various positions of the drainage gallery. The optimal position of the drainage gallery is obtained which results in the lowest hydraulic uplift force. Similarly, study is done for other objectives of the research.

3.4 RELIABILITY OF THE RESEARCH WORK

The reliability of the research work is done by comparing the results obtained from the numerical model with the results of empirical formula by USBR and empirical relation based on experimental data of physical model (El-Razek et al, 2001). Since the USBR formula does not consider the position of drainage gallery and due to the smaller size and other constraints of the physical model, a good agreement in their results is not expected.

4 ANALYSIS, RESULT AND DISCUSSION

4.1 ANALYSIS AND RESULT

The simulation results of the proposed model were analyzed and the results of the analysis are summarized in this chapter with some discussion on the response of the model to the applied hydraulic field.

4.1.1 Response of the model

The response of the model in terms of pore pressure and total discharge velocity is obtained. From these results, the hydraulic uplift force along the base of the dam and the discharge occurring into the drain holes are calculated. The results were compared for the various positions of the drainage gallery and final recommendation for the suitable position of the drainage gallery is made, within the limitations of the proposed model.

4.1.2 Variation of Hydraulic Uplift Force with Water Head

The variation of hydraulic uplift force caused by the seepage of water due to the ponded water at the upstream of the dam varies linearly with the head of water available at the dam upstream.

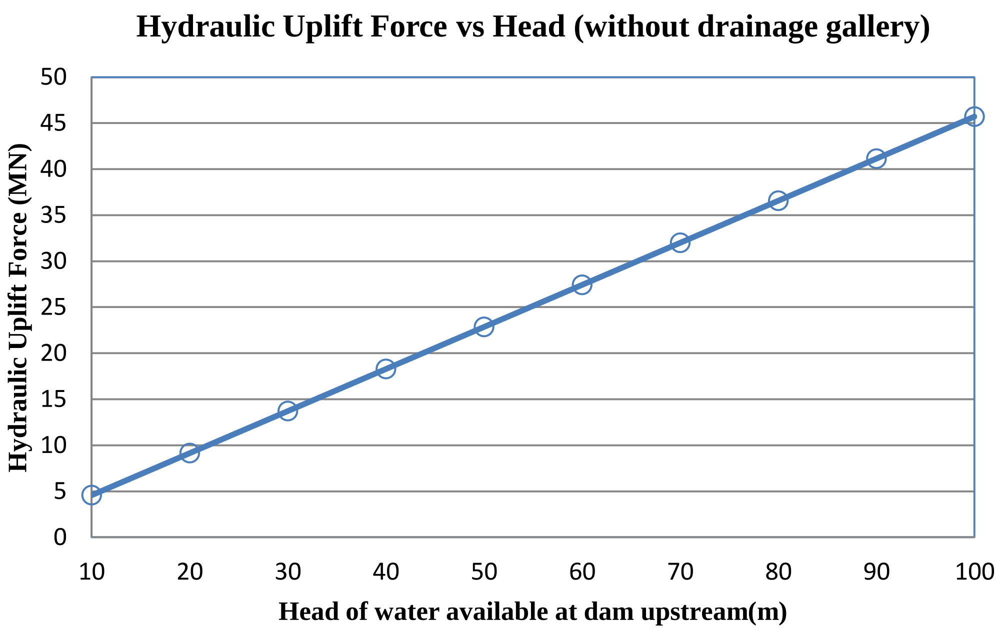

Figure 4-1: Variation of Hydraulic uplift force with available head (no drainage)

The plot of hydraulic uplift force and head of water available at the dam upstream shows that the hydraulic uplift force is maximum in the case of no drainage gallery provided in the dam, and minimum if the drainage gallery is provided at 20% of base width from upstream of the dam. The relation between hydraulic uplift force and head of water available at dam upstream is linear.

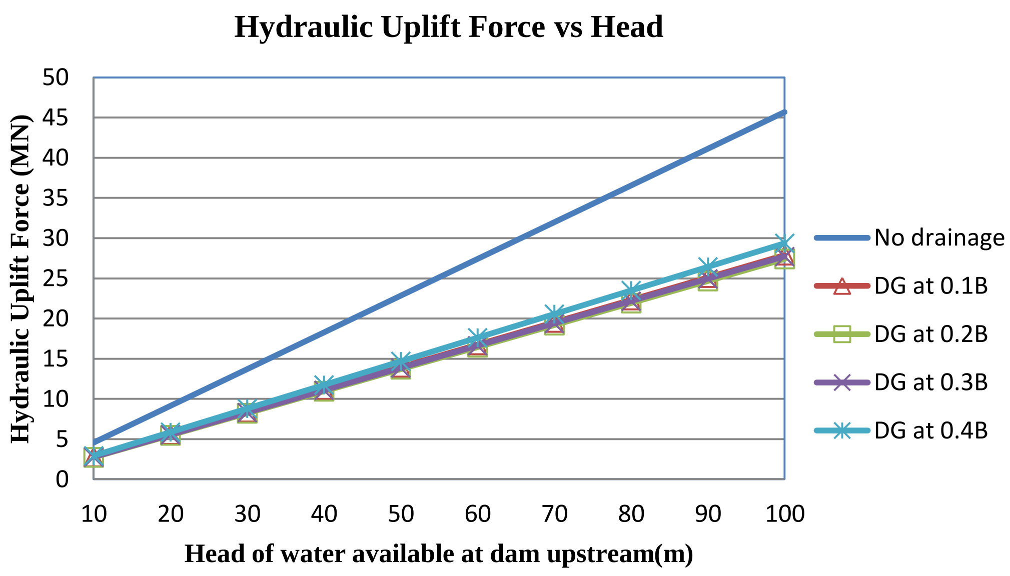

Figure 4-2: Variation of Hydraulic uplift force with available head

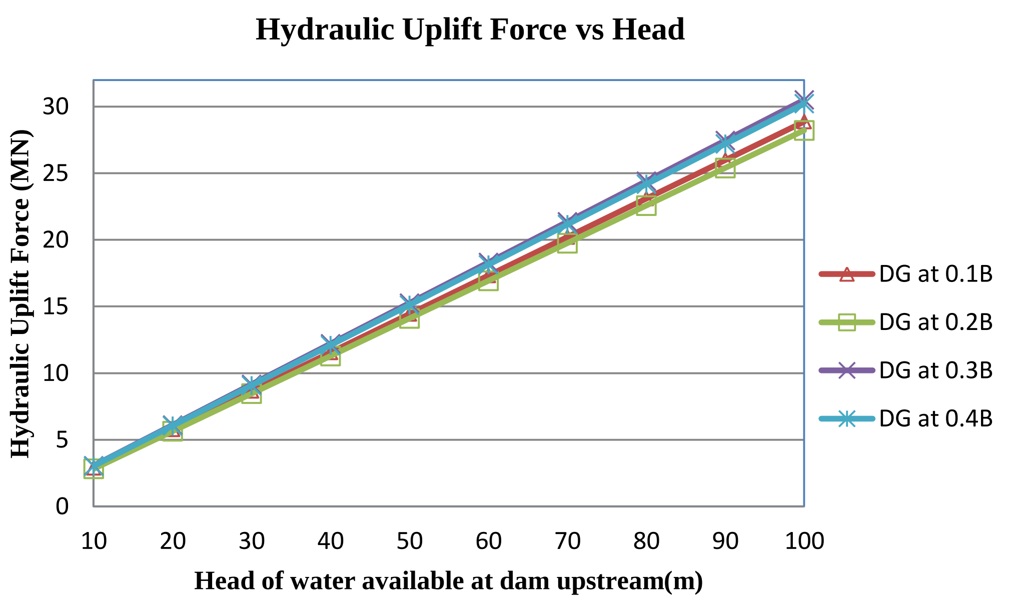

Figure 4-3: Variation of Hydraulic uplift force with available head (for drainage galleries)

4.1.3 Variation of Pore Pressure along the base of the dam

The plot of pore pressure versus distance along base of the dam shows that the pore pressure is maximum at upstream side of the dam base and minimum i.e. zero, since no downstream water level is considered in this case, at downstream side of the dam base. The pore pressure is almost linear at the middle portion of the dam, but near upstream and downstream end of the dam base, an abnormal release and accumulation of the pore pressure is seen. This is due to the non-linear variation of head along the dam base in the simulation results.

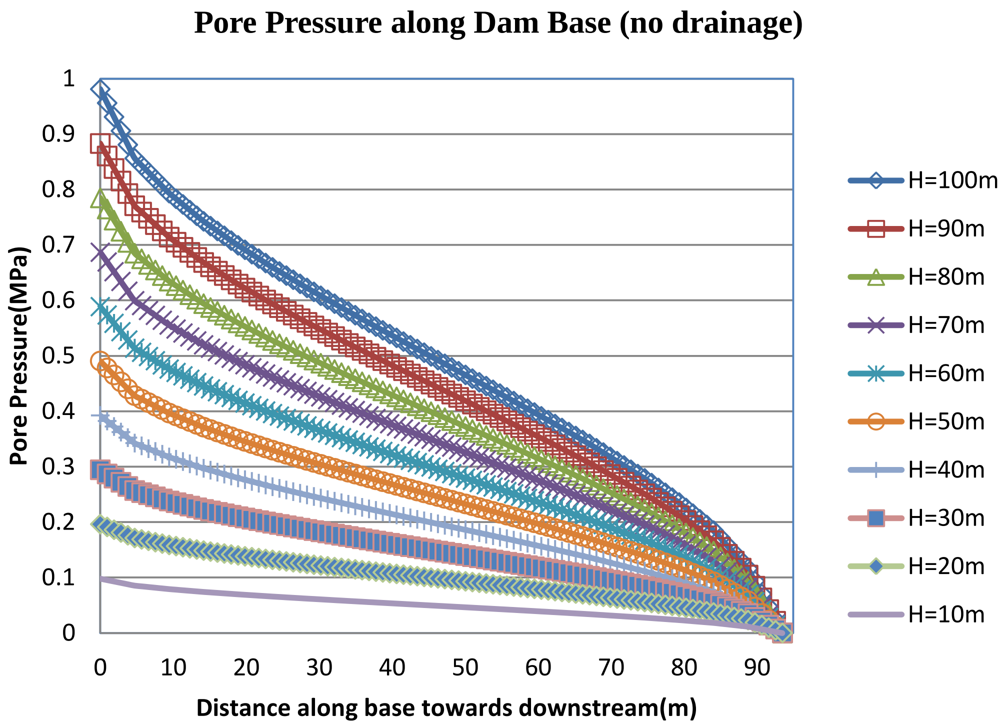

Figure 4-4: Variation of Pore pressure along base of the dam for different heads

The variations of pore pressure along base of the dam are shown in the graphs from figure 4-5 to figure 4-8. The pore pressure drops to zero at the drainage hole in the base of the dam, from maximum at the upstream edge of the dam. From drainage hole the pore pressure increases towards the downstream side for some distance and then decreases to the zero at the downstream edge where no downstream water is considered.

The plot of pore pressure with all position of drainage gallery is also shown in graphs from figure 4-5 to figure 4-8.

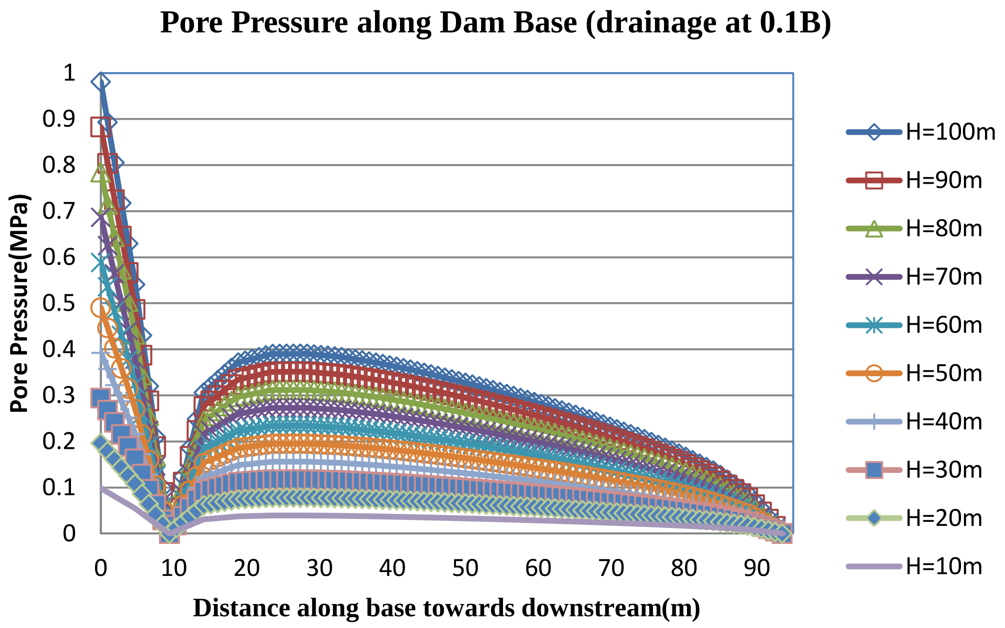

Figure 4-5: Variation of Pore Pressure along base of the dam with drainage gallery at 10% of base width distance from upstream face of dam

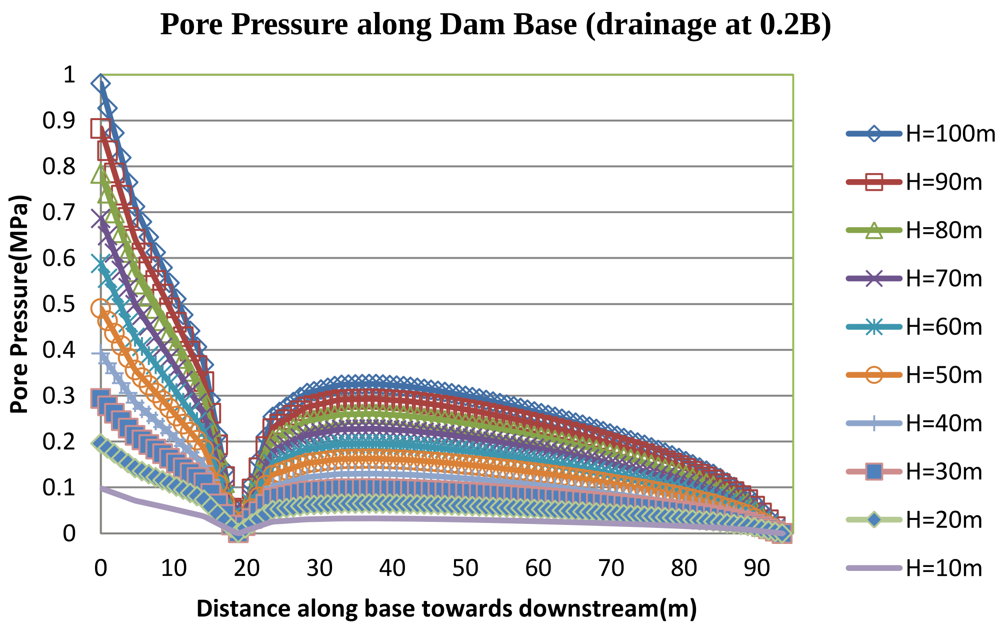

Figure 4-6: Variation of Pore Pressure along base of the dam with drainage gallery at 20% of base width distance from upstream face of dam

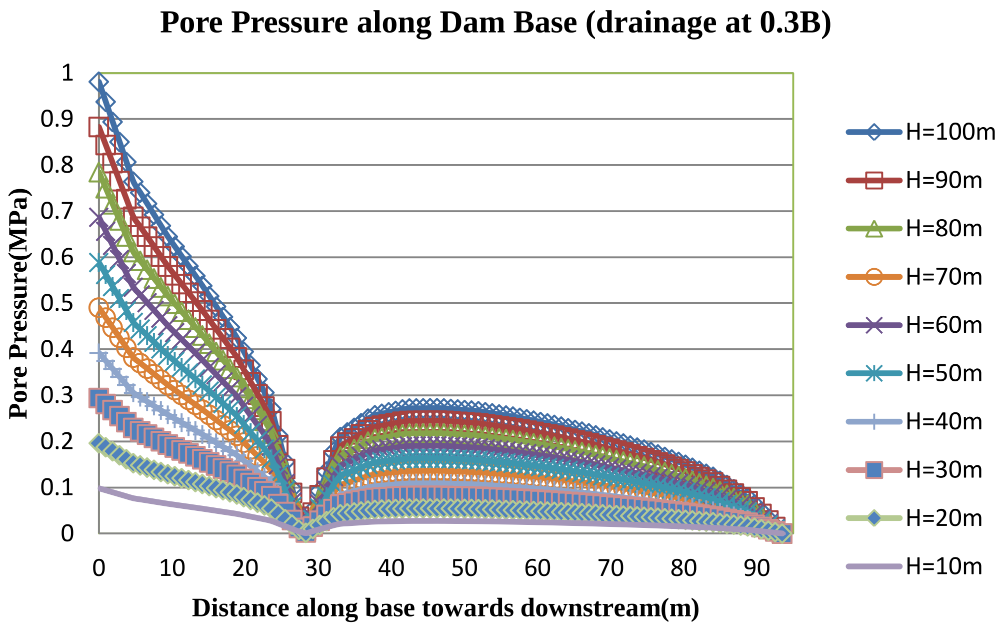

Figure 4-7: Variation of Pore Pressure along base of the dam with drainage gallery at 30% of base width distance from upstream face of dam

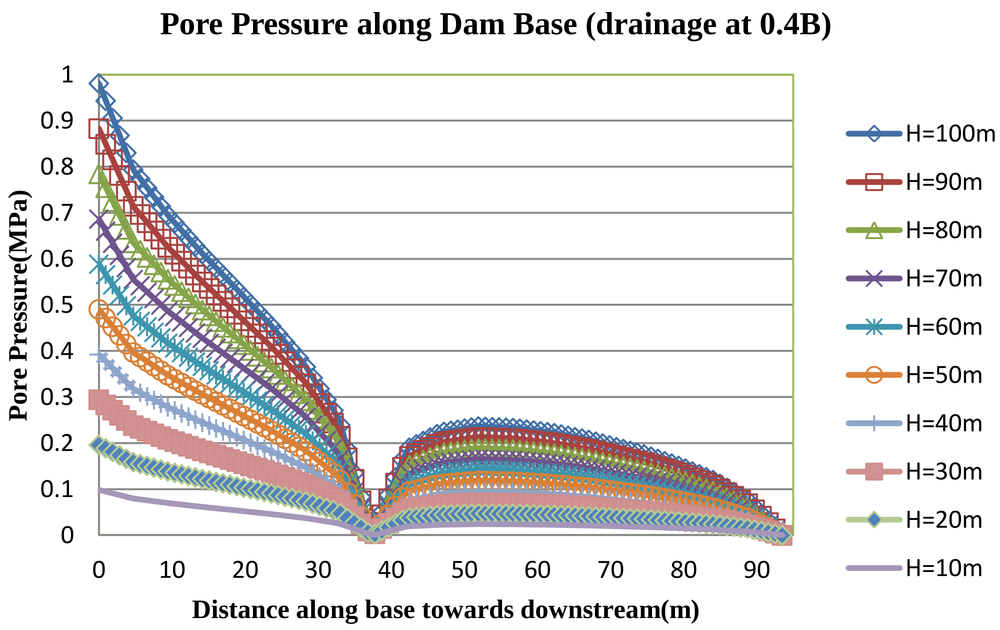

Figure 4-8: Variation of Pore Pressure along base of the dam with drainage gallery at 40% of base width distance from upstream face of dam

4.1.4 Variation of Pore Pressure for different position of drain

The variation of pore pressure along the base of the dam for no drainage gallery and for drainage gallery at different distances from upstream face is shown in the graph figure 4-9. It can be seen that there is huge amount of reduction in the pore pressure due to the presence of the drainage gallery. It is also noted that the shifting of drainage gallery towards further downstream side of the dam increase the pore pressure towards the upstream side of the drainage gallery and decreases the pore pressure towards the downstream side of the drainage gallery from the shifted position of the drainage gallery. The best position of the drainage gallery is recommended where the overall hydraulic uplift force acting over the base of the dam is minimum.

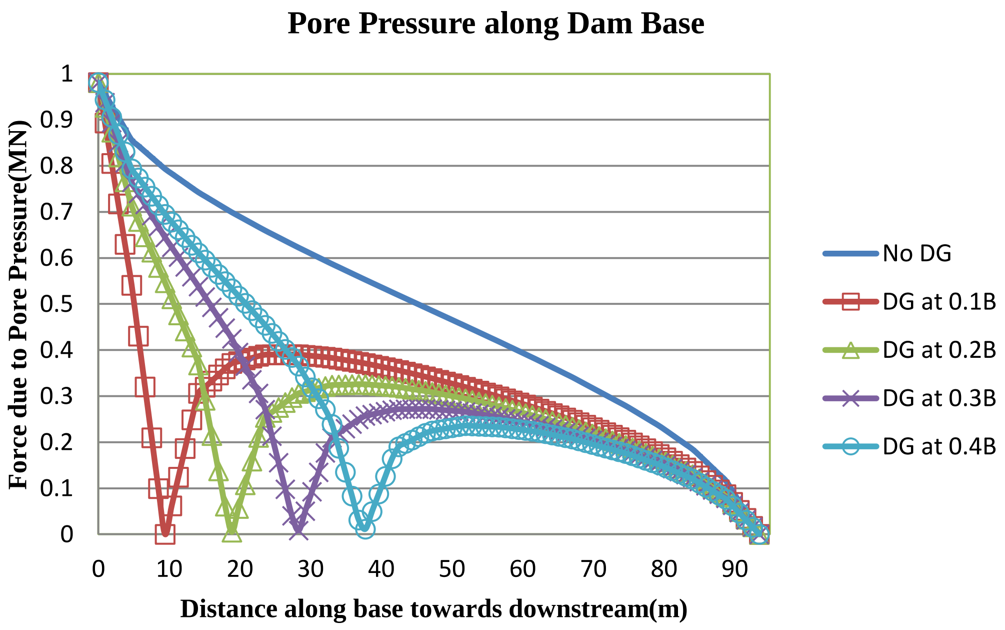

Figure 4-9: Variation of Pore Pressure along base of the dam without drainage gallery and with drainage gallery at various positions

4.1.5 Variation of Reduction Factor (RF) with position of drain

The plot of reduction factor of hydraulic uplift force for different position of drain with head of water available at the upstream side of the dam is shown in the graph figure 4-10. It can be seen that the reduction factor is constant for a certain position of the drain, irrespective of the water head available at the upstream side of the dam. The reduction factor is maximum for the placement of drain at 20% distance of the base width and minimum (among these four positions of the gallery) for the placement of drain at 40% distance of the base width from upstream face of the dam. The maximum reduction factor obtained at 20% distance of base width depends upon the effective head i.e. the difference in water level at upstream and downstream portion of dam. In the considered case, the effective head is 100m, for no downstream water level.

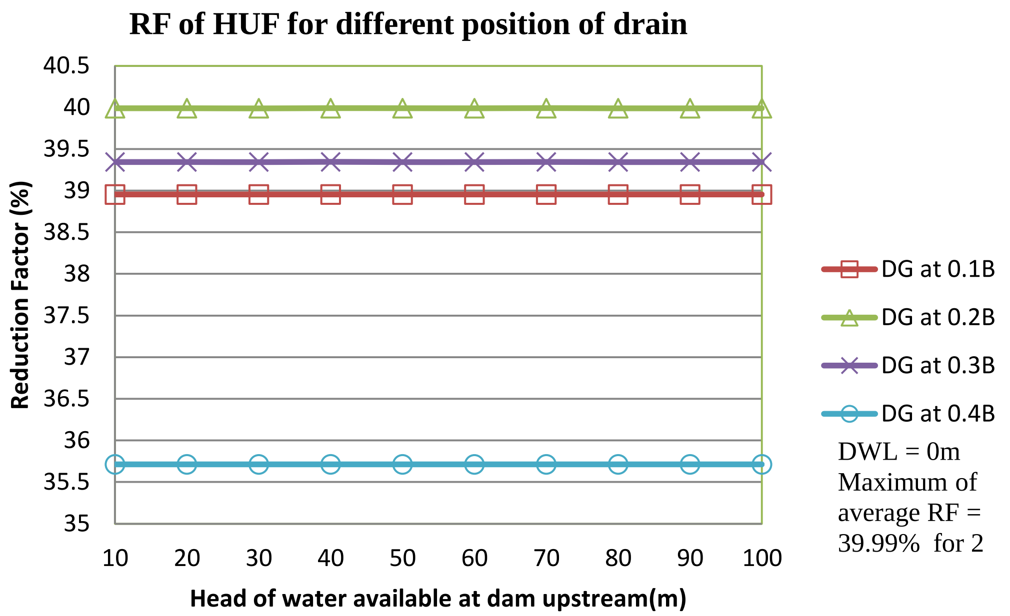

Figure 4-10: Variation of Reduction Factor (RF) with position of drain and head of water at dam upstream

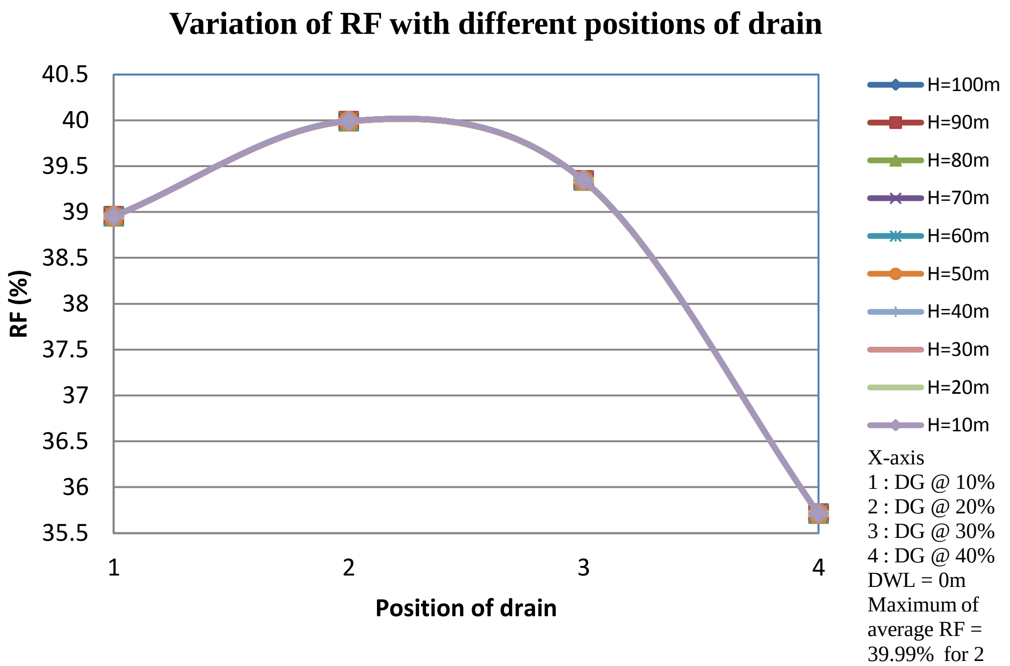

Figure 4-11: Variation of Reduction Factor (RF) for different positions of drain

4.2 EFFECT OF DOWNSTREAM WATER LEVEL

In the presence of downstream water level, the variation of hydraulic uplift force with the head of water available at the upstream face of the dam has similar nature as that for the case of no downstream water level. However, the hydraulic uplift force has increased considerably due to the presence of water at downstream side of dam. The minimum hydraulic uplift force is observed for the placement of drainage gallery at 20% base width of dam from upstream face of the dam, for no downstream water level.

The variation of hydraulic uplift force with head of water available at upstream when downstream water level is 5m is shown in the graph Figure 4-12. It shows considerable reduction in hydraulic uplift force due to the provision of drainage gallery.

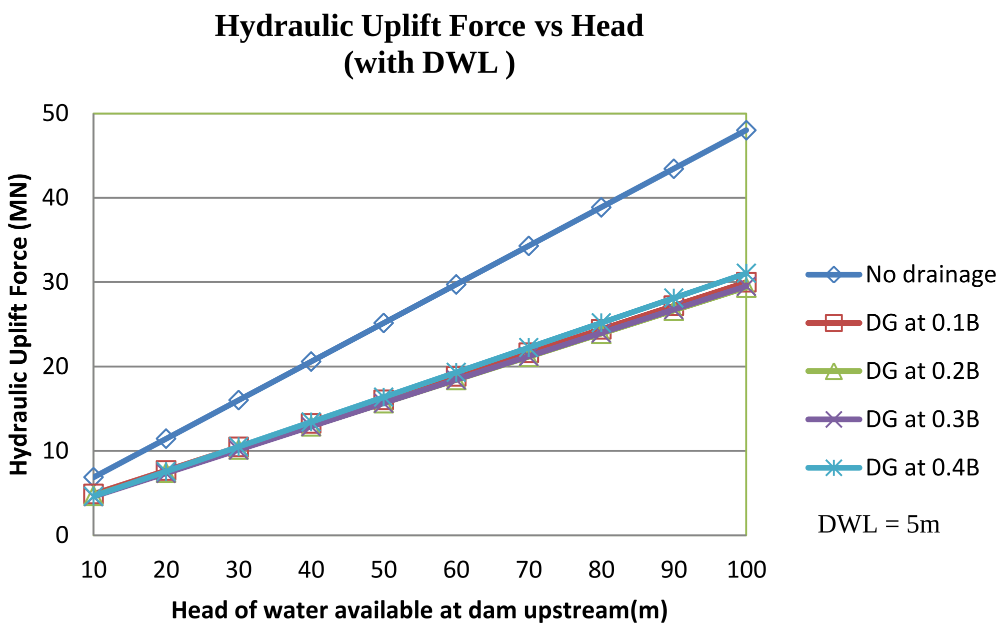

Figure 4-12: Variation of Hydraulic uplift force with available head for downstream water level

4.2.1 Variation of Reduction Factor with the position of drain

For studing the variation of reduction factor with the position of the drain, different models were prepared with increasing downstream water level from 0m to 20m, with 5m interval. From the graphfigure 4-13, it is shown that the reduction factor of hydraulic uplift force is maximum for drainage gallery at 30% of base width from upstream face, for lower heads of water available at the upstream side of the dam(i.e. for heads less than 50m). Whereas the reduction factor is maximum for drain at 20% of base width from upstream face of dam for higher heads of water available at the upstream side of the dam (i.e. for heads more than 50m). This is due to the change in line of action of the resultant hydraulic upthrust force with increase in downstream water level. As the head of downstream water level rises in the dam, the line of action of the resultant of hydraulic upthrust force moves further downstream along the base of the dam, which requires the shifting of the drainage gallery further downstream in the body of the dam.Similar observations can be drawn from other graphs provided for various downstream water levels.

The maximum of average reduction factor for each case is also calculated, which is provided along with the graph. The location of drainage gallery with maximum of average reduction factor is recommended for each case.

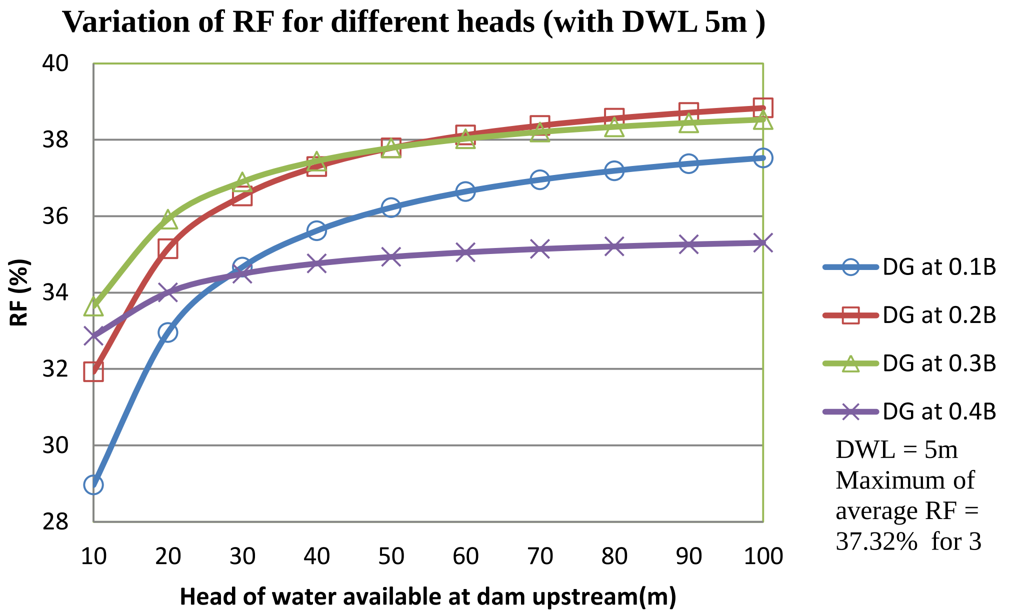

Figure 4-13: Variation of RF for various heads at dam upstream with downstream water level of 5m

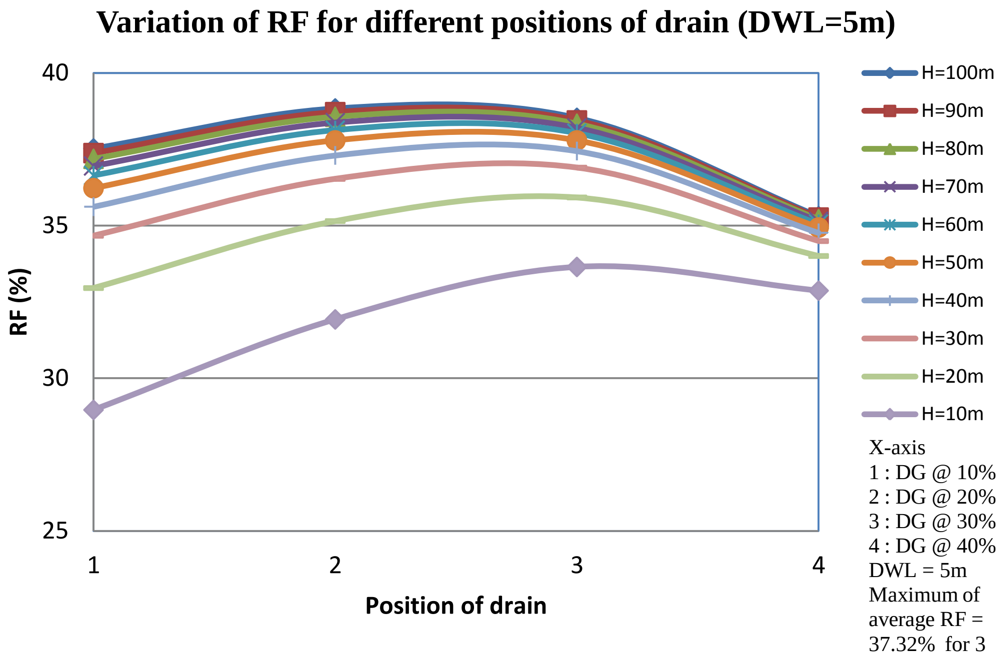

Figure 4-14: Variation of RF for various positions of drainage gallery with downstream water level of 5m

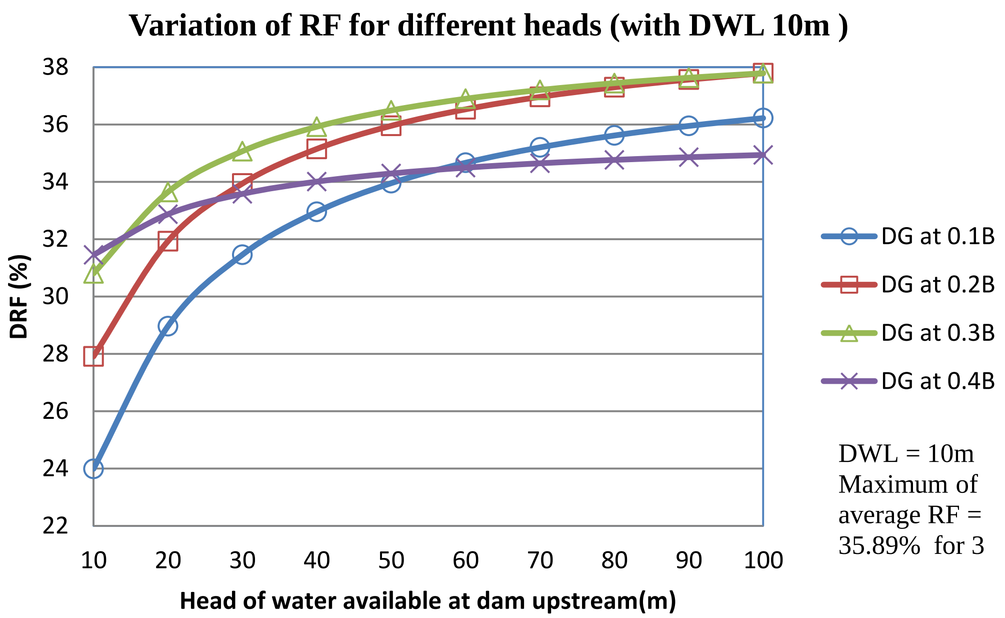

Figure 4-15: Variation of RF for various heads at dam upstream with downstream water level of 10m

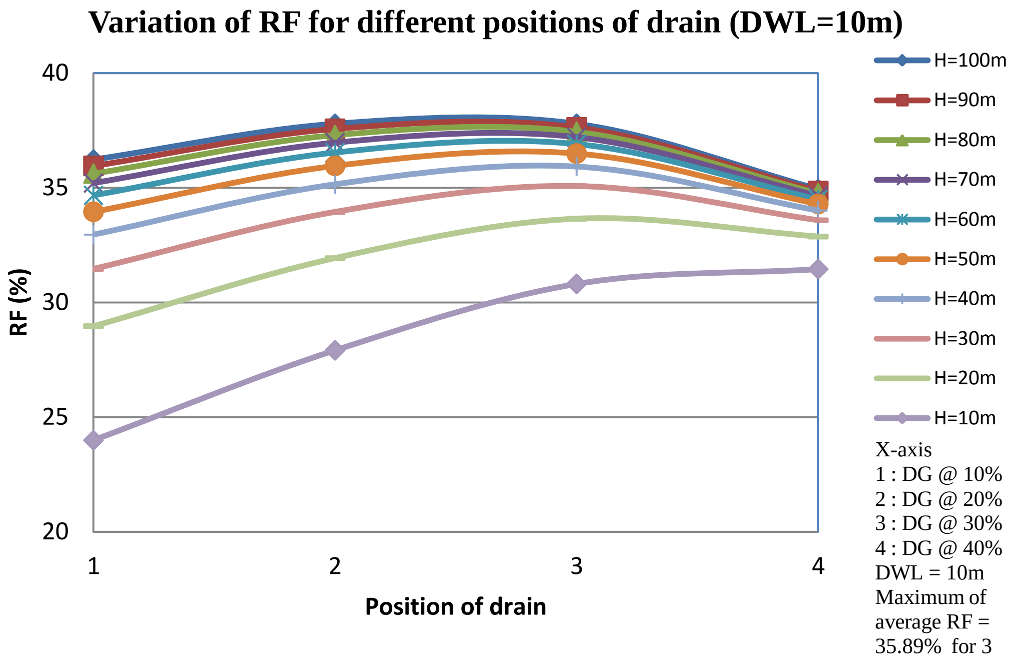

Figure 4-16: Variation of RF for various positions of drainage gallery with downstream water level of 10m

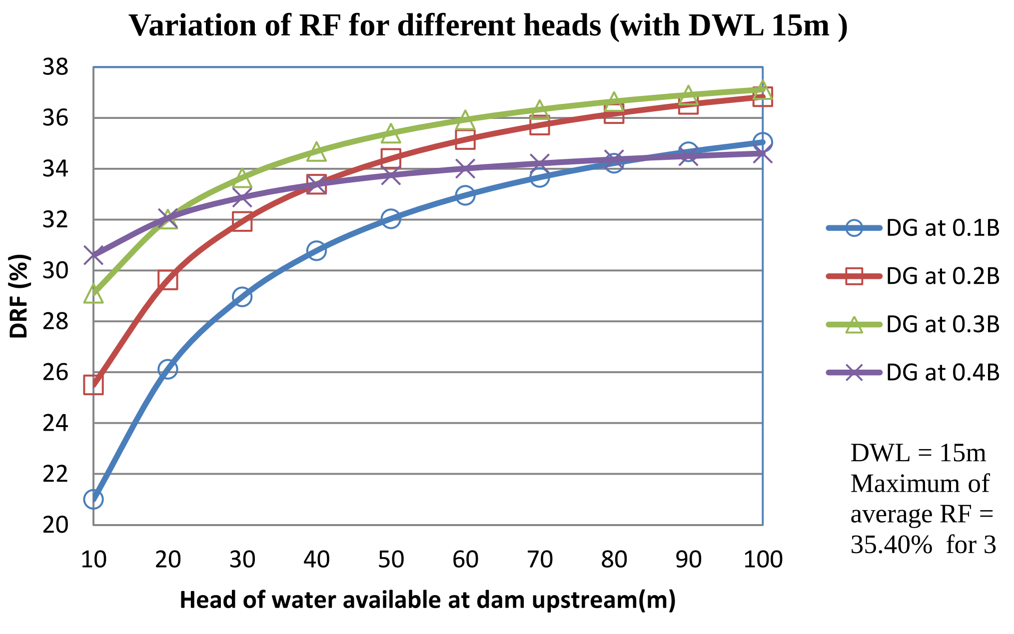

Figure 4-17: Variation of RF for various heads at dam upstream with downstream water level of 15m

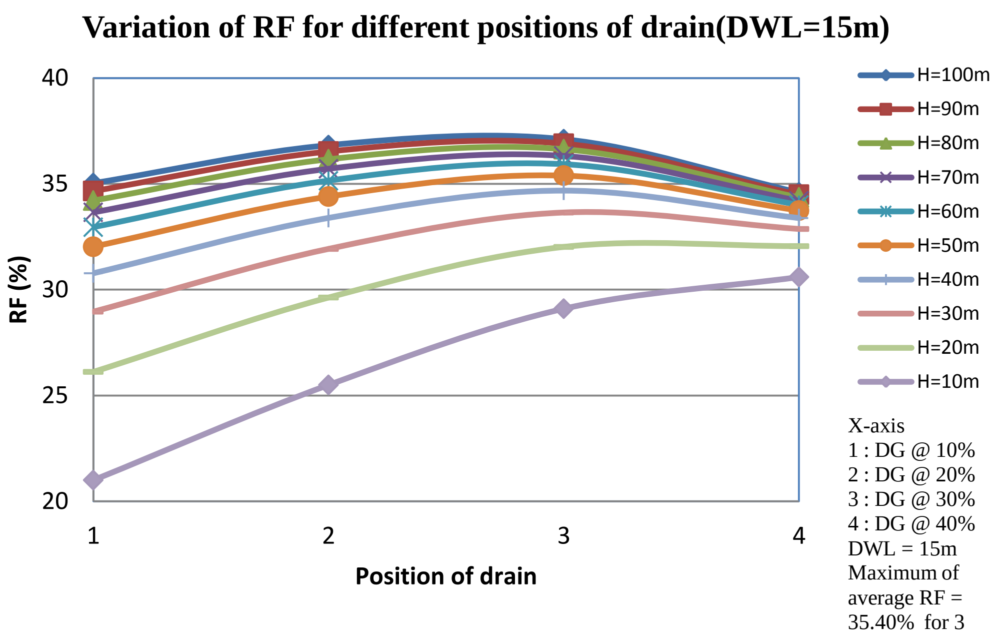

Figure 4-18: Variation of RF for various positions of drainage gallery with downstream water level of 15m

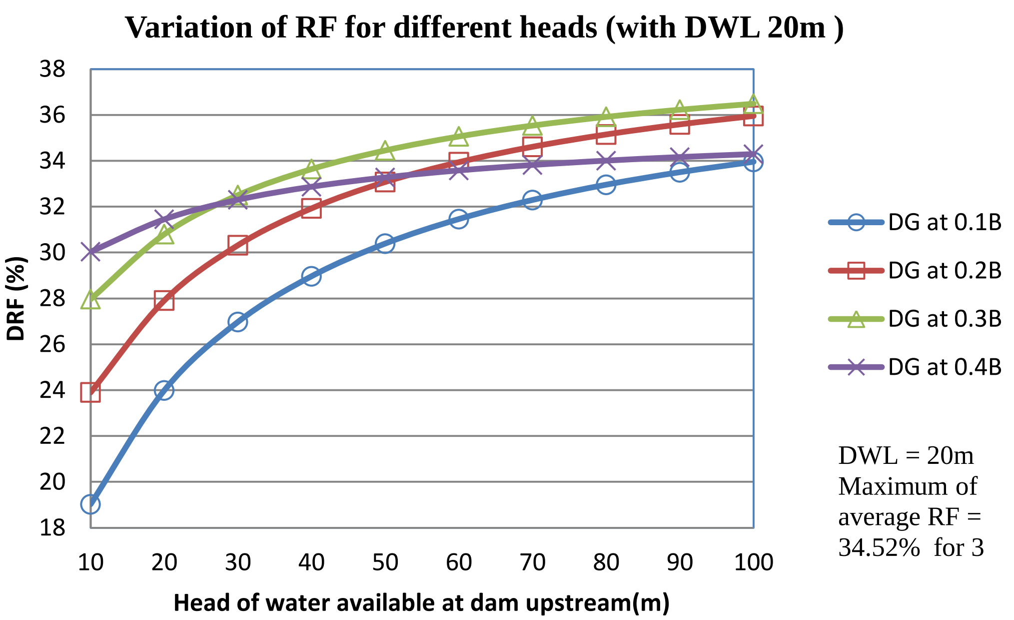

Figure 4-19: Variation of RF for various heads at dam upstream with downstream water level of 20m

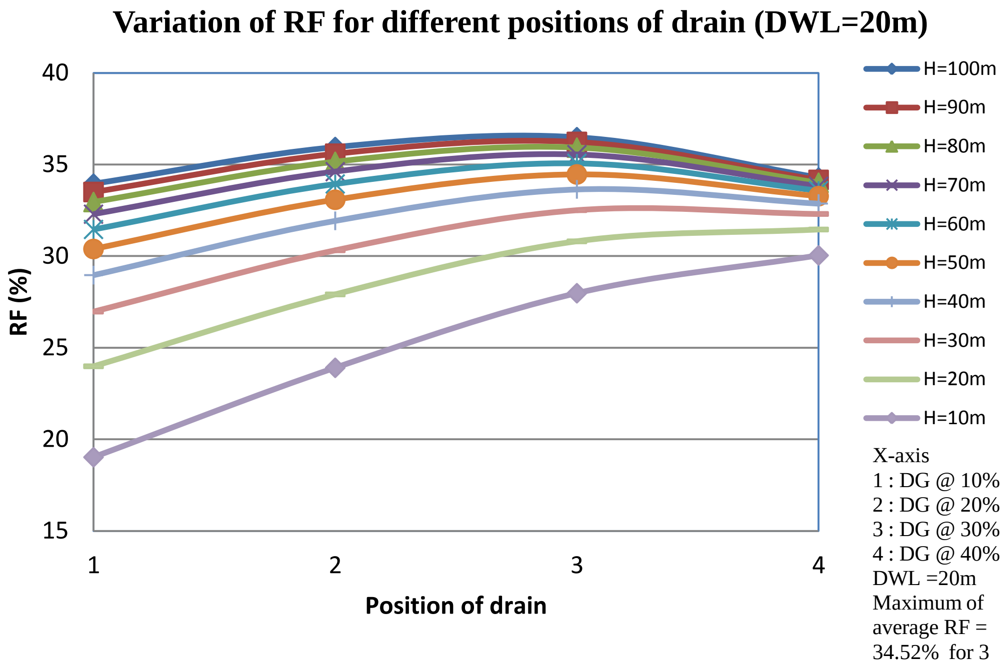

Figure 4-20: Variation of RF for various positions of drainage gallery with downstream water level of 20m

4.2.2 Variation of Hydraulic Uplift Force due to downstream water level

From the plot of hydraulic uplift force versus head of water available at dam upstream for downstream water level of 5m and no downstream water level, it is seen that the hydraulic uplift force increase with the presence of downstream water level. The plots for other downstream heads is also similar.

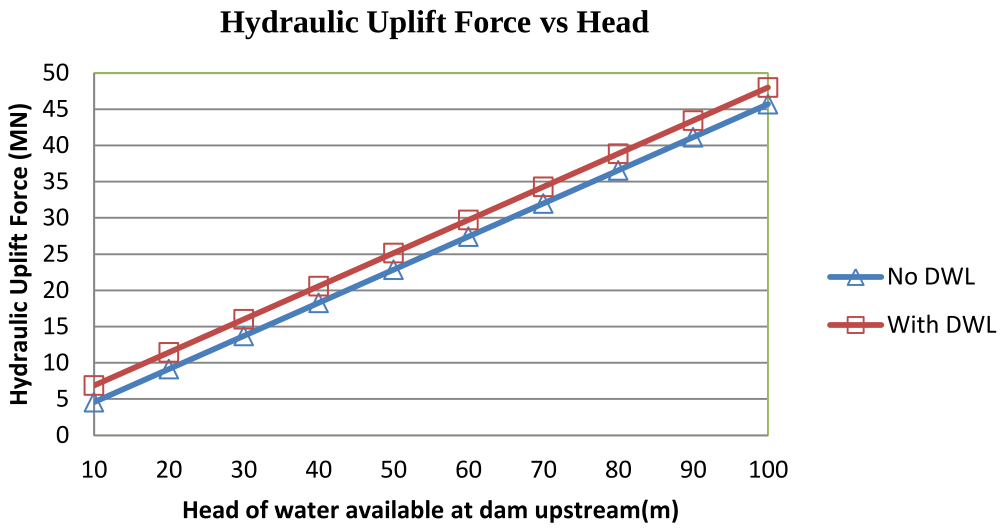

Figure 4-21: Variation of hydraulic upthrust force along base of the dam with and without downstream water

4.2.3 Variation of Pore Pressure with downstream water level

The change in pore pressure along the base of the dam due to the presence of downstream water level is shown in the graph figure 4-22. Due to the presence of downstream water level, the change in pore pressure is maximum at the downstream portions of the base whereas very minor change is observed at the upstream portions of the base of the dam. The cases of downstream water level of 5m are shown in the graphs Figure 4-22 and Figure 4-23.

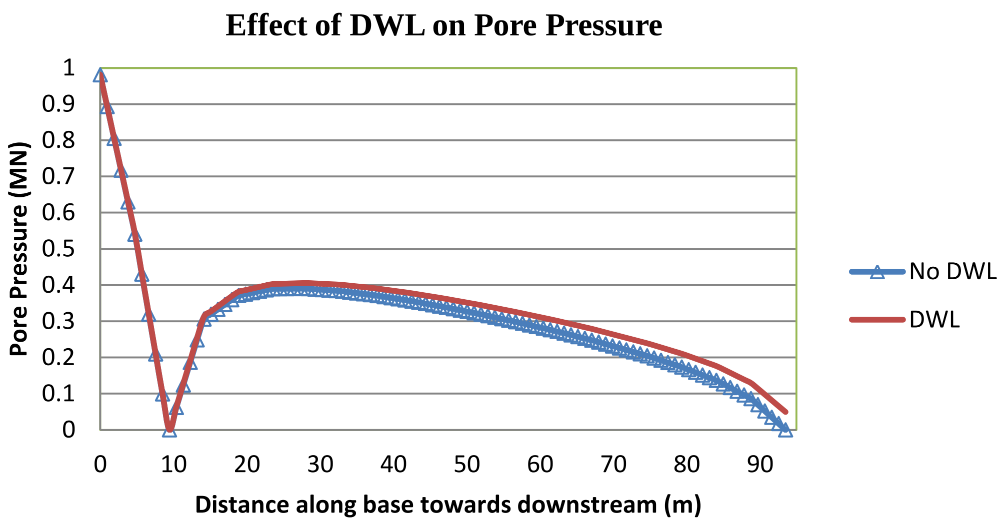

Figure 4-22: Variation of Pore Pressure along base of the dam with and without downstream water

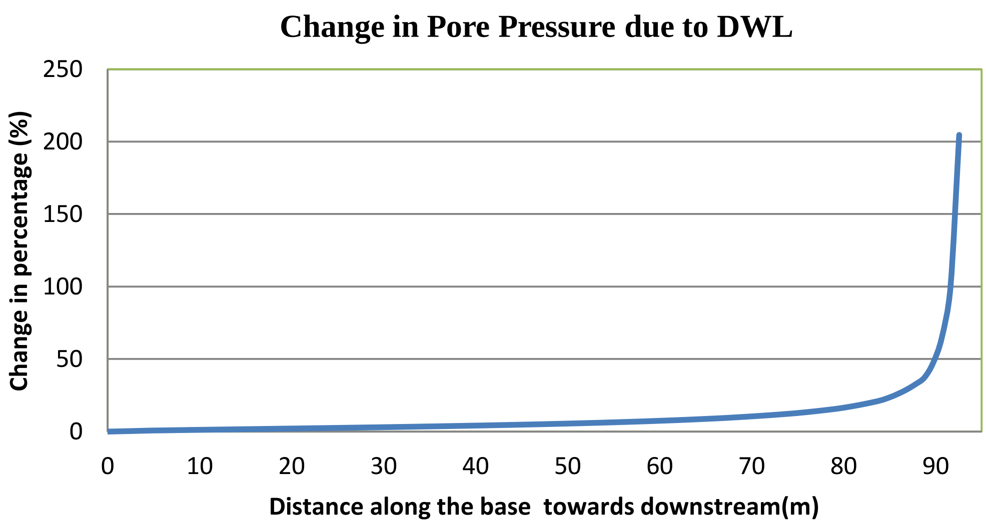

Figure 4-23: Variation of change in Pore Pressure along base of the dam due to downstream water

4.3 EFFECT ON FACTOR OF SAFETY

The effect of drainage gallery on the factor of safety (FoS) is also studied. The factor of safety against sliding is calculated according to IS: 6512-1984 (Criteria for Design of Solid Gravity Dams, First Revision). The FoS for upstream water height of 100m and downstream water height of 0m is calculated for different positions of drainage gallery.

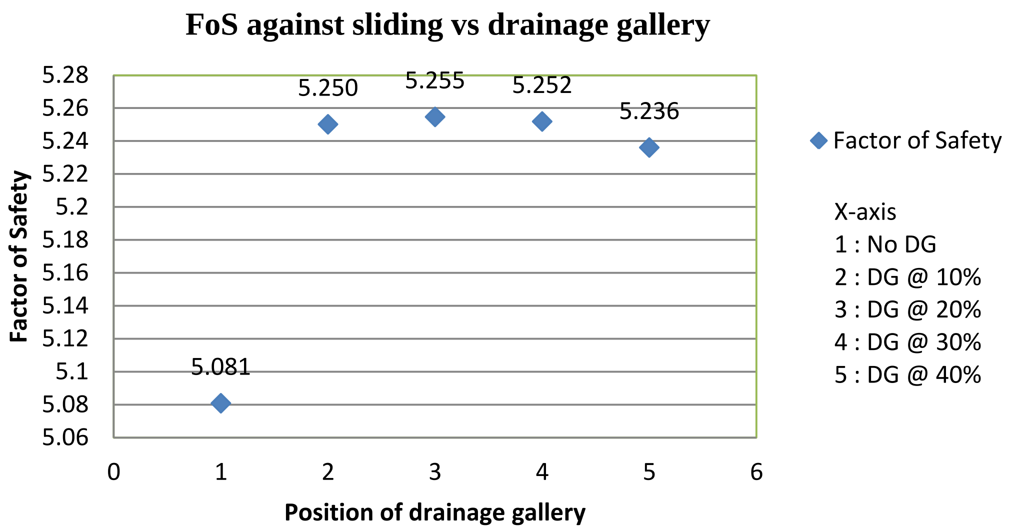

Figure 4-24: Variation of factor of safety (FoS) against sliding versus position of the drainage gallery

Similarly, the factor of safety against overturning is calculated.

From the plot of factor of safety (FoS) versus position of drainage gallery, it can be seen that the FoS against sliding and overturning is increased when drainage gallery is provided in the dam. Also, the factor of safety (FoS) varies for the various position of the drainage gallery. The maximum factor of safety against sliding is obtained as 5.255 for the position of drainage gallery at 20% of base width of the dam. And the maximum factor of safety against overturning is obtained as 4.2696 for the position of drainage gallery at 20% of base width of the dam.

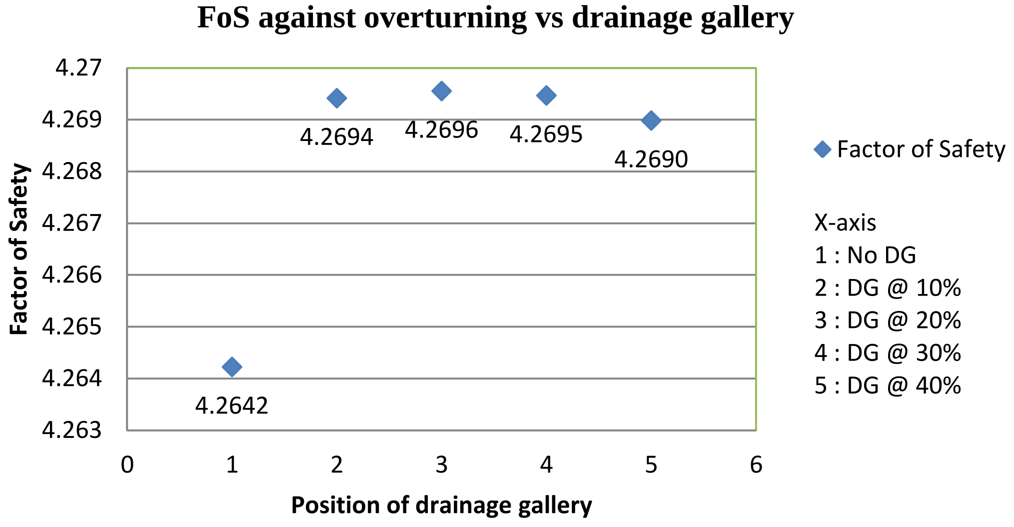

Figure 4-25: Variation of factor of safety (FoS) against overturning versus position of the drainage gallery

4.4 DISCHARGE OCCURING INTO SINGLE DRAIN HOLE

The discharge into a single drain hole is calculated. The drain hole is modeled according to the IS: 10135-1985(Code of Practice for Drainage System for Gravity Dams, their Foundations and Abutments, First Revision).

From the graph of figure 4-26, it is seen that discharge into drain holes are increased with increasing height of water at dam upstream and decreases with increasing distance from the upstream face of the dam. The relation between discharge and available head is linear due to its linearity with the total head loss.

Similarly, in the plot of variation of discharge and uplift with the distance along dam base in figure 4-27, it can be seen that the discharge is non-linearly related with the distance along the dam base. This non-linear relation can be explained with the fact that the loss of head occurring at the base of dam is non-linear with the distance along the base of the dam. Also the hydraulic uplift force has a minimum value, at 20% of dam base from upstream face of the dam. On placement of the drainage gallery at this position, the incoming discharge into the gallery is also less than placing it at 10% of base width. Hence, by shifting the position of the drainage gallery from distance of 10% to 20% of the dam base, not only the hydraulic uplift force will decrease but also the incoming discharge will decrease, which will require a smaller section of gutter drain in the drainage gallery. Hence, it will not only lead to a safer design but also an economic design.

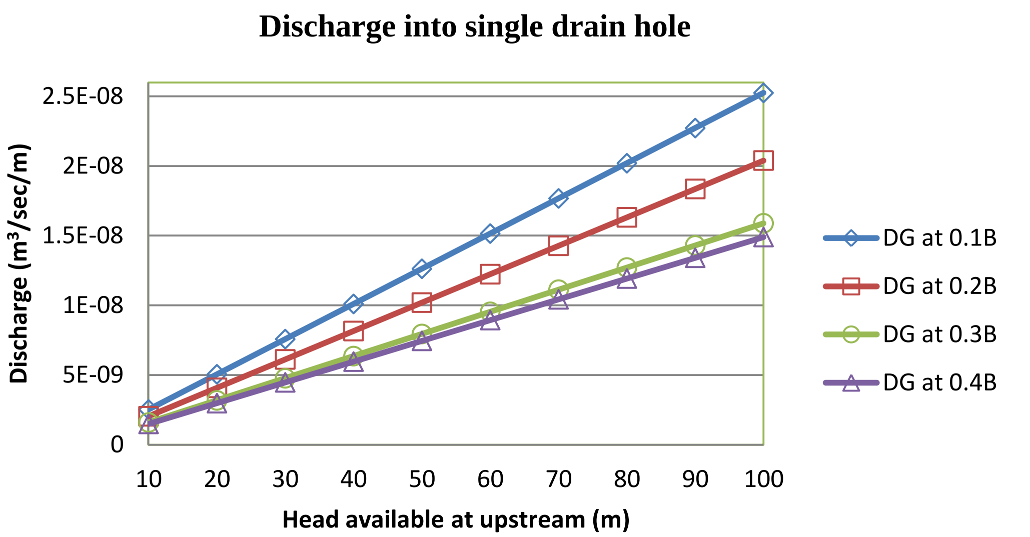

Figure 4-26: Variation of discharge into the single drain hole with the water head available at the dam upstream

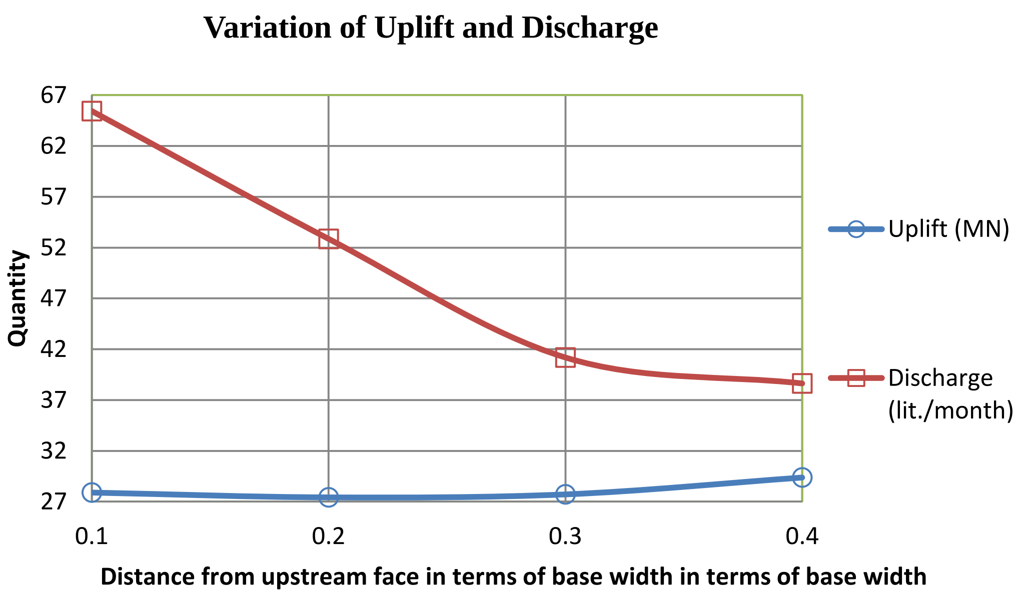

Figure 4-27: Variation of discharge into the single drain hole and uplift force for various positions of drainage gallery

4.5 EFFECT OF THE HEIGHT OF THE DRAINAGE GALLERY

The effect of the height of the drainage gallery on hydraulic uplift force is studied. The hydraulic uplift force increases with the increasing height of the drainage gallery. So the minimum height of the drainage gallery is recommended for minimizing the uplift force, and hence increasing the factor of safety. As specified in IS 12966 (Part1):1992 (Code of Practice for Galleries and Other Openings in Dams), there should be minimum 1.5m concrete cover between the floor of the gallery and the foundation grade. If due to the foundation grade profile and other considerations like the height of the dam from foundation grade up to the spillway crest in respect of overflow section, gallery deposition in other blocks, etc, a foundation gallery will have to be located into trench, a minimum concrete cover of about 2.0m is generally recommended.

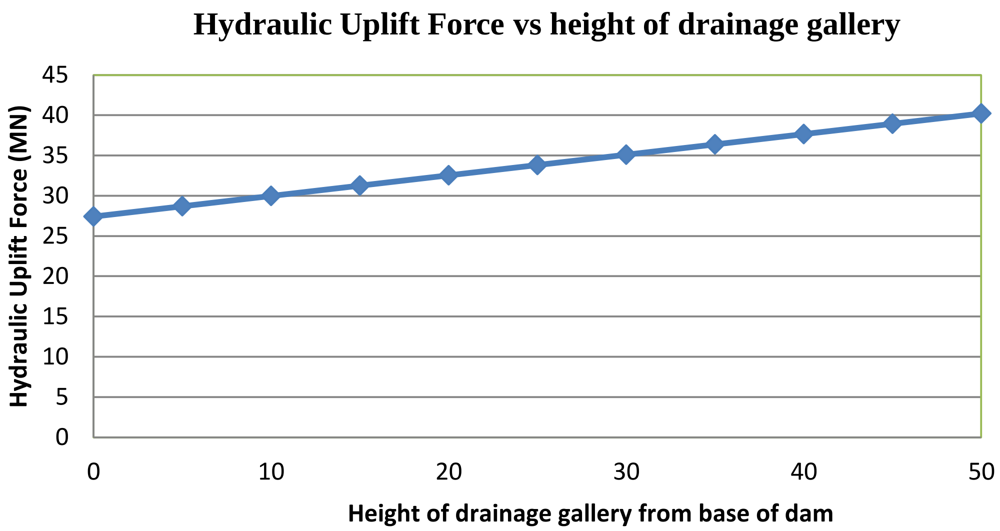

Figure 4-28: Variation of hydraulic uplift force with the height of the drainage gallery

4.6 EFFECT OF THE SIZE OF THE DRAIN HOLES

The size of the drain hole is modeled for 100mm, according to the IS: 10135-1985(Code of Practice for Drainage System for Gravity Dams, their Foundations and Abutments, First Revision). The effect of the size of the drain holes is also studied by changing the size of the drain holes. The size of the drain holes are varied by increasing and decreasing the size by 20%, 40% and 60%.

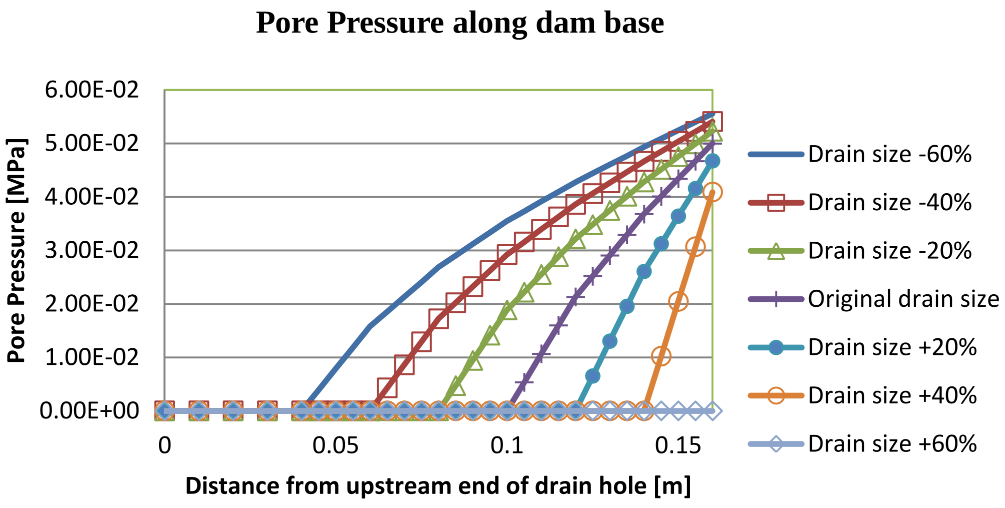

Figure 4-29: Variation of Pore Pressure with the size of the drainage gallery

From the plot of pore pressure versus size of drain hole, it is seen that the pore pressure increases beyond the drain hole. At any vertical section, beyond the drain hole, larger size of the drain hole will give lower value of pore pressure.

Also from the plot of discharge versus size of drain hole in figure 4-30, it can be seen that the increase in size of the drain holes increases the discharge into the drain holes

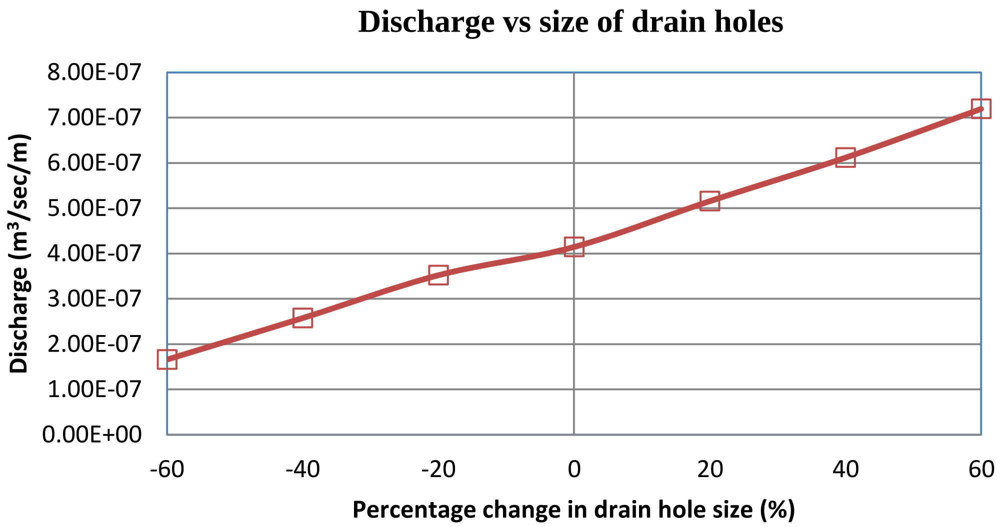

Figure 4-30: Variation of discharge with the size of drainage gallery

Also, the effect of variation of size of drain holes on the number of drain holes provided per unit meter of drainage gallery is studied. For determining the number of drain holes required per unit length of drainage gallery, the size of drain hole and the height of the drainage gallery is kept as per IS 10135:1985(Code of Practice for

Drainage System for Gravity Dams, their Foundations and Abutments, First Revision) and IS 12966(Part1):1992 (Code of Practice For Galleries and Other Openings in Dams). The number of drain holes required for the given model is 4 per meter for draining the incoming discharge into the drain holes if the gallery is to be provided at the optimum position (at a distance of 20% of the base width of the dam from upstream face of the dam and height of 1.5m), with the given assumptions of the model.

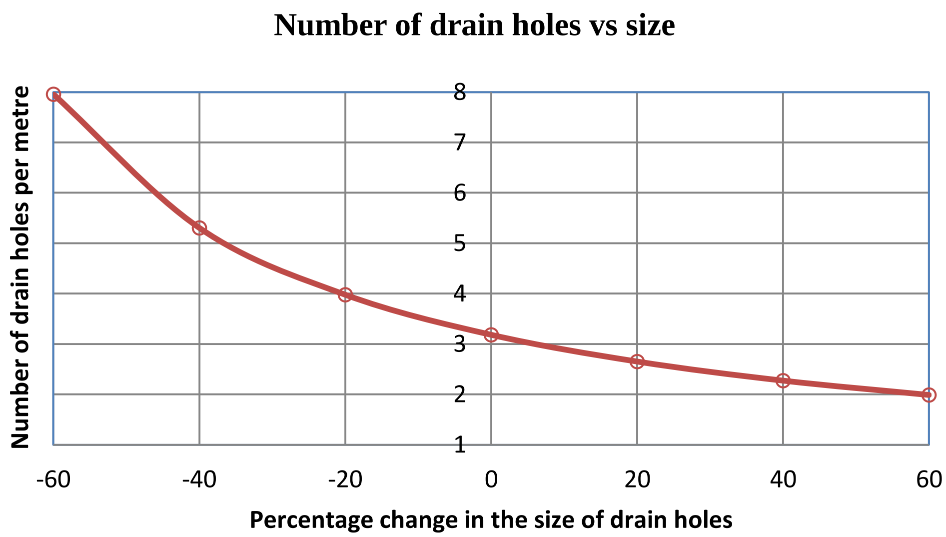

Figure 4-31: Variation of number of drain holes per unit length of drainage gallery with the size of drain holes

4.7 EFFECT OF THE DEPTH OF THE DRAIN HOLES

The effect of the depth of the drain holes is also studied. As per IS 10135:1985(Code of Practice for Drainage System for Gravity Dams, their Foundations and Abutments, First Revision), the depth of the holes may be kept between 20 and 40 percent of the maximum reservoir depth for the preliminary design. So the depth of the drain holes is kept as 20m, 30m and 40m from the base of the foundation. It can be seen from the plot of pore pressure along dam base in graphs of figure 4-35, figure 4-36 and figure 4-38, that the maximum reduction in the overall pore pressure in achieved if the depth of drain holes is kept at 40m. From the plots of discharge versus depth and uplift versus depth in figure 4-33 and figure 4-34, it is seen that the maximum discharge and minimum hydraulic force occurs for the deepest drain hole of 40m. Hence deeper drains are more effective in reducing the hydraulic uplift force acting on the dam, for the homogeneous and isotropic conditions of the rock foundation.

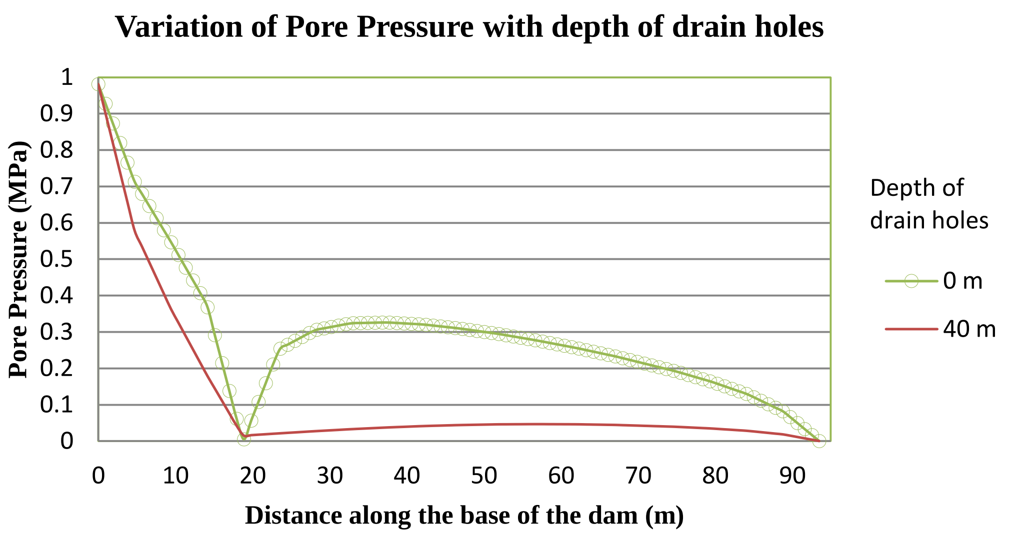

figure 4-37

Figure 4-32: Variation of pore pressure with depth of drain holes

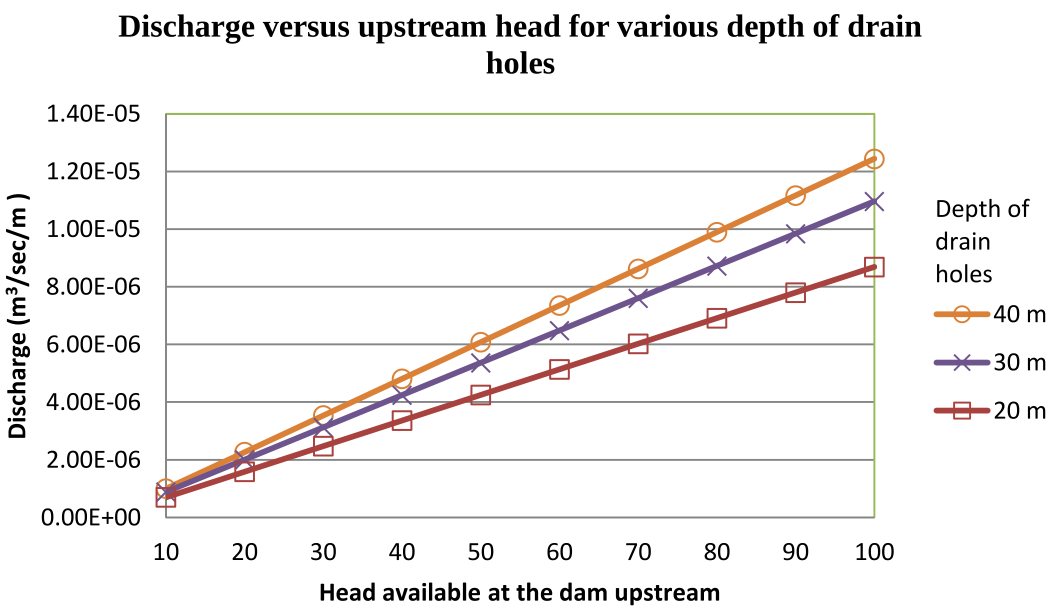

Figure 4-33: Variation of discharge with upstream head for various depths of drain holes

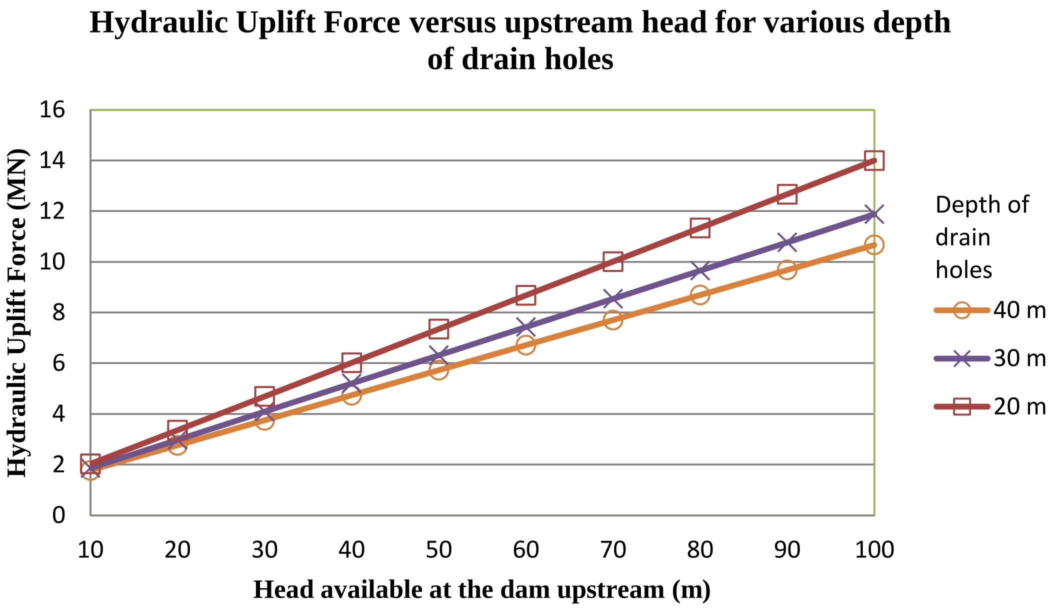

Figure 4-34: Variation of hydraulic uplift force with upstream head for various depths of drain holes

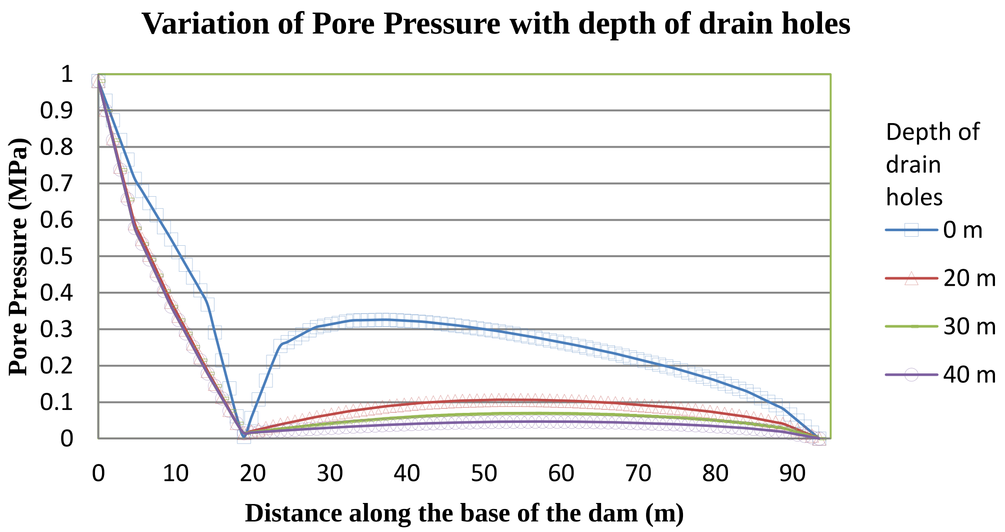

Figure 4-35: Variation of pore pressure with depth of drain holes

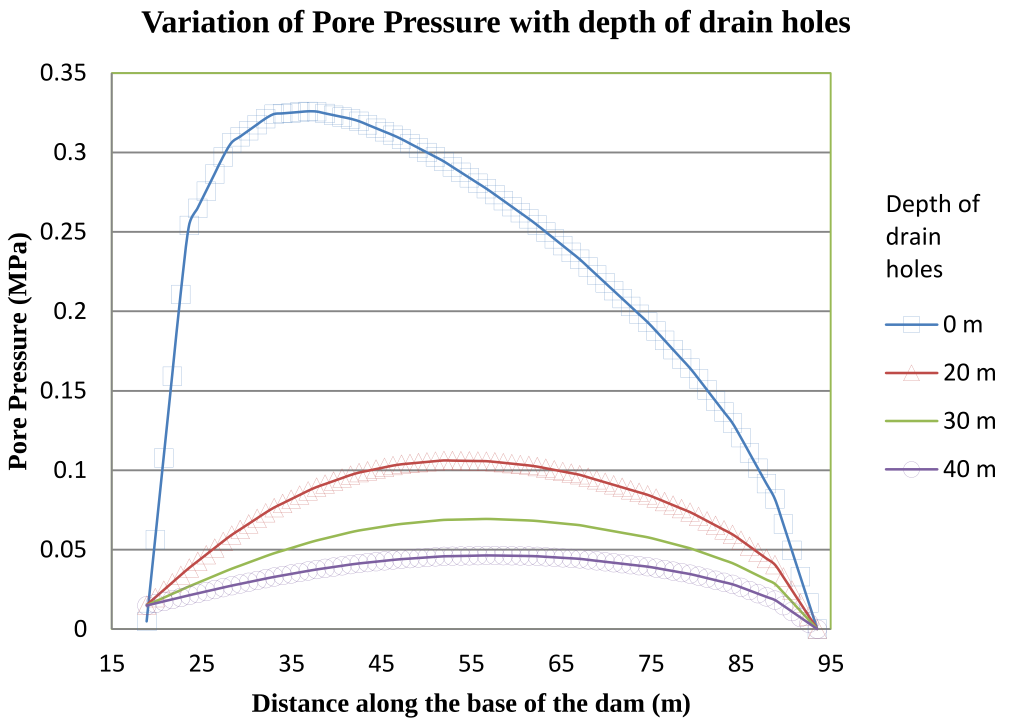

Figure 4-36: Variation of pore pressure with depth of drain holes from drainage gallery to downstream of dam

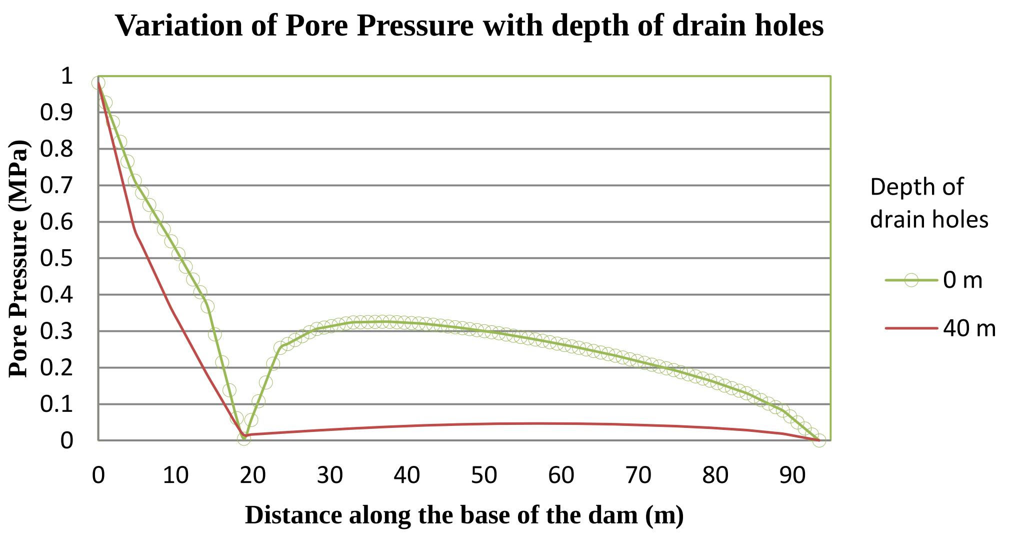

Figure 4-37: Variation of pore pressure of the deepest hole of the model

5 RELIABILITY OF THE RESEARCH WORK

5.1 RELIABILITY OF THE RESEARCH

The reliability of the research work is carried out by comparing the simulation results of the numerical model with the empirical formula proposed by U.S. Bureau of Reclamation (USBR) and the empirical formula proposed by the study of physical model of El-Razek et al (2001). Since the empirical formula of USBR does not consider the position of drainage gallery and due to the smaller size and other constraints of the physical model, a good agreement of their results is not expected. Although, it can be seen that the relation proposed by USBR is more accurate for the placement of drainage gallery at 30% of base width of the dam from toe, with downstream water available.

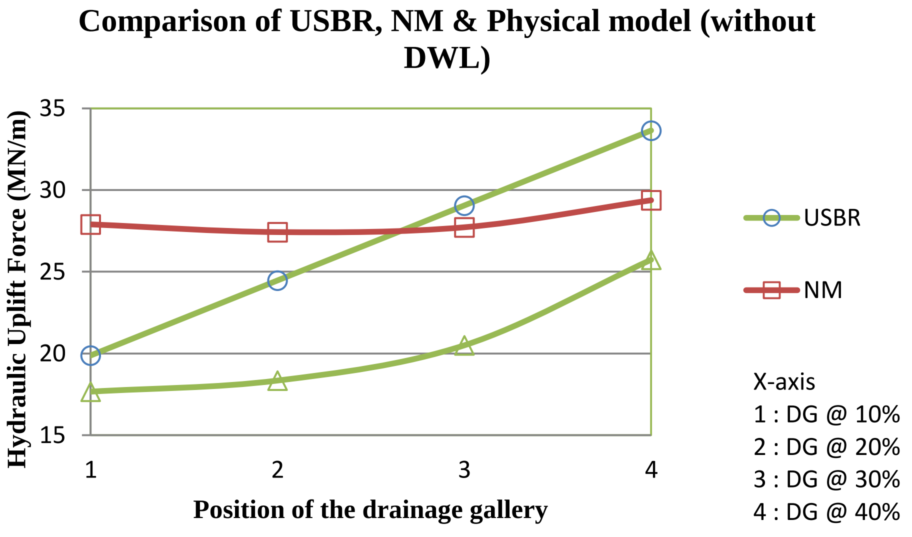

Figure 5-1: Comparison of USBR, NM & Physical model (without DWL)

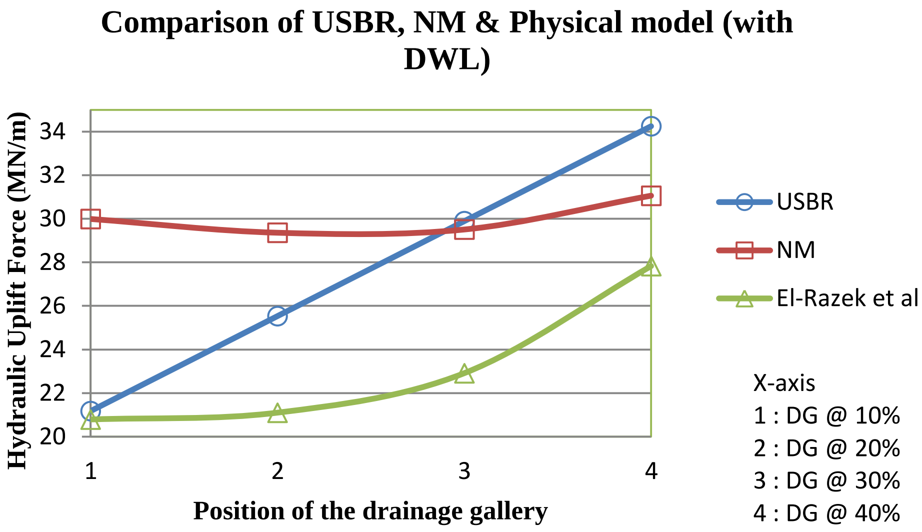

Figure 5-2: Comparison of USBR, NM & Physical model (with DWL)

The comparison between then USBR formula, physical model (El-Razek et al, 2001) and the proposed numerical model can be more conveniently made by the plot of deviation percentage of USBR formula and empirical relation of the physical model from the proposed numerical model. The plots for no downstream water and with downstream water are shown in figure 5-3 and figure 5-4 respectively.

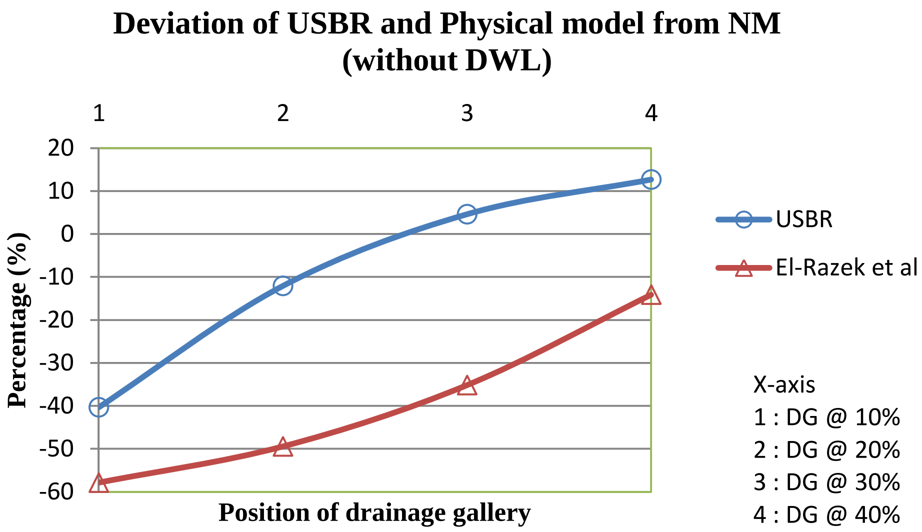

Figure 5-3: Deviation of USBR and PM from NM (without DWL)

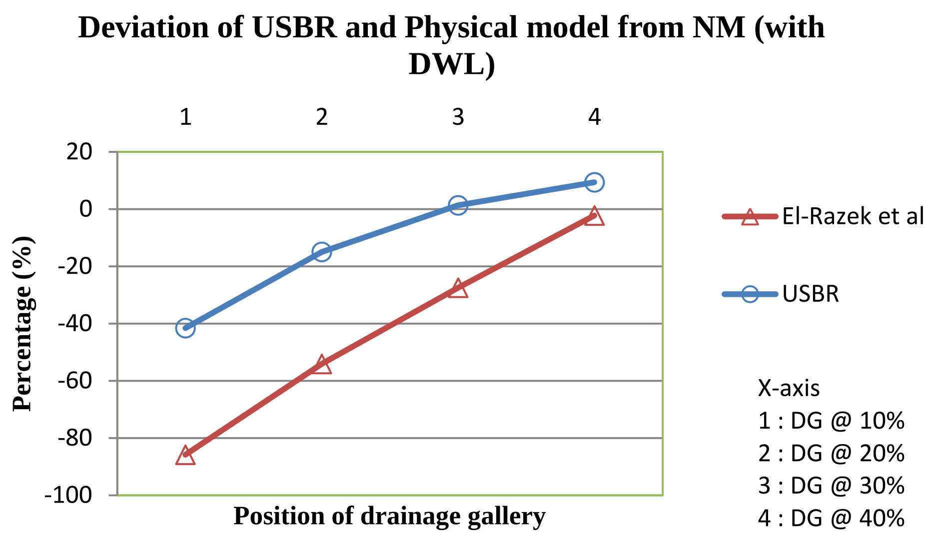

Figure 5-4: Deviation of USBR and PM from NM (with DWL)

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The conclusions drawn from the numerical modeling of location optimization of the drainage gallery are as follows:

- The hydraulic uplift force has a linear relation with available head at the upstream portion of the dam.
- The hydraulic uplift force has a non-linear relation with the distance along the dam base.
- The drainage gallery significantly decreases the pore pressure if placed at a proper place inside the dam body.
- For no downstream water, the optimum distance of the drainage gallery is obtained at 20% of the base width from upstream face, with 39.99% reduction factor in uplift force.
- For downstream water levels of 5m, 10m, 15m and 20m, the optimum distance of drainage gallery is obtained at 30% of the base width from upstream face, with 37.32%, 35.89%, 35.40% and 34.52% reduction factor respectively, in the uplift force.
- The reduction in the uplift force achieved with the provision of drainage gallery depends upon the dimensions of the dam, water levels maintained at the upstream and downstream of the dam and the height of the gallery from base of the dam.
- The number of drain holes required per meter of gallery is four, for the optimized position of drainage gallery in the given numerical model.
- The increase in downstream water level increases uplift, significantly towards the toe portion of the dam.
- The provision of drainage gallery increases the factor of safety (FoS).
- The maximum increase in FoS is 3.44% for sliding (5.255 at 0.2B) and 0.14% for overturning (4.27 at 0.2B), after providing drainage gallery at optimized position in the given model.
- The hydraulic uplift force exerted on the dam is minimum at 20% of base width of dam (27.42 MN for the numerical model).

- The discharge into a single drain hole decreases with increasing distance from the dam heel. This discharge has non-linear relation with distance from heel of the dam.
- The hydraulic uplift force increases with the increase in the height of the drainage gallery. So the height of only required concrete cover should be provided, if suitable.
- The increase in drain hole size results in increase of discharge into drain and decrease of spacing of the drain holes.
- The increase in drain hole depth results in increase of discharge into drain and decrease of hydraulic uplift force on the dam.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

The recommendations for future research are as follows:

- The study can be carried out with three dimensional models which can better simulate the drainage effect of the drain holes.
- The effect of drainage gallery in the rock foundation, for the reduction of hydraulic uplift force on dam, can be studied.
- The effect of multiple drainage galleries for the reduction of hydraulic uplift force can be studied.
- The effect of inclination of the drain holes on the effectiveness of drainage can be studied.
- The effect of fracturing of the rock foundation can be studied.
- The effect of anisotropic permeability of the material model can be studied.
- The spacing of the drain holes can be accurately obtained from the three dimensional model, which will lead to better optimization of the drainage system. So, it can be studied.
- If instrumentation data are available, a reduction factor can be proposed for the intermediate positions between drain holes of the drainage gallery, to simulate the three dimensional drainage effect in two dimensional model.
- The effect of size of the model on the simulation results can be studied.
- The effect of the porous concrete can be studied.
- The results of the numerical model can be verified with the field data.

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