NUMERICAL ANALYSIS OF SEEPAGE OF DIAMER BASHA DAM

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No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the National University of Sciences and Technology (NUST) in partial fulfillment of the requirements for the degree of Master of Science in field of Geotechnical Engineering from NUST institute of Civil Engineering (NICE), School of Civil and Environmental Engineering (SCEE), NUST.

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I, Rizwan Khan, declare that the MS thesis I have submitted titled "Numerical Analysis of seepage of Diamer Basha Dam" is my original work and has not been submitted previously to the National University of Sciences and Technology Pakistan or any other institution in the country or abroad. If at any point it is discovered that my statement is untrue, even after I have graduated, the university is authorized to revoke my MS degree.

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MY BELOVED PARENTS

WHO GAVE ME A LOT OF SUPPORT

AND

ENCOURAGEMENT

ACKNOWLEDGEMENT:

All glory to Great Allah, Who blessed me with knowledge and enlightenment to carry out this research work. I would like to express sincere gratitude to my supervisor Dr. Tariq Mahmood Bajwa for his unprecedented enthusiasm, constructive critique and valuable discussions. Without his support and guidance, completion of this project would not have been possible.

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ABSTRACT:

A dam is a hydraulic structure, constructed across a water channel for water pondage, which is used for various purposes, such as flood control, irrigation, navigation, sedimentation control and hydro-power generation.Like other components deformation and sseepage analyses are integral part of dam design, requiring key attention from engineers, scientists and researchers considering its safety perspectives. If seepage and deformations are not properly controlled, the dam structure fails causing significant human and financial losses. Therefore, this study investigates the seepage and deformation behaviour of a dam using SEEP/W and SIGMA/W finite element models. The data of Diamer Basha dam is used for this purpose. This dam is a roller compacted concrete gravity dam, lying on rock foundation. The data for material properties and geometry of dam for analysis was obtained from consultants. Boundary conditions were chosen very carefully. The data regarding the loads applied in the model including upstream hydro-static pressure, downstream hydro-static pressure, uplift pressure and self-weight were also collected from the available research reports.The seepage is examined using steady state and transient conditions for the reservoir levels at normal operational level (minimum, maximum) and safety check flood level. Various scenarios of grout curtain and reservoir levels have been investigated for deformation analysis. The study is quite useful as the dam under study is tall one and it provides several useful recommendations to the industry practitioners.

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LIST OF SYMBOLS / ABBREVIATIONS

WAPDA	Water and Power Development Authority
RCC	Roller compacted concrete
FEM	Finite element modelling
MAF	Million acre-foot
BCM	Billion cubic meters
MW	Mega watts
GWH	Giga watts hertz
asl	As per sea level
FWO	Frontier Works Organization
JV	Joint venture
U/S	Up stream
D/S	Down stream
GPa	Giga Pascal
i	Gradient of specific hydraulic head
q	Specific discharge
1-D	One dimensional
cu yd.	Cubic yards
k_{hx}	Hydraulic conductivity in X direction
Sat.	Saturated
Vol.	Volumetric

Chapter # 1

1. Introduction

1.1. General:

A dam is a hydraulic structure, which is built across the water streams for multipurpose functions, such as water storage, flood control and hydropower generation. There is always a need of new dams to fulfill human needs and to satisfy the socioeconomic purposes. The research work reports the seepage and stress analysis of Diamer Basha dam, which is under-construction on Indus River, at Chilas, Pakistan. Stress analysis and seepage analysis are needed for the reasons that over-stressing of the dam materials may cause their crushing or fracturing and seepage phenomenon may leads to over-turning or piping phenomenon, which eventually causes failure of the part or the whole dam structure. For these reasons, these analyses are integral part of dam design, which demands key attention from engineers and scientists considering its safety perspectives.

In preliminary studies, literature review is done about possibility of seepage and impact of deformations upon stability of RCC gravity dams, followed by analysis of similar case studies for the aforementioned purposes. For the data concerned with analysis, it is needed to collect that from WAPDA (Water and Power Development Authority). Hence, site visit to Diamer Basha dam is made and data is collected from WAPDA. For the numerical analysis, SEEP/W is used for seepage analysis and SIGMA/W is used for stress analysis.

1.2. Background and scope:

As seepage analysis is an important part of dam safety and stability. Therefore, it needs to be properly analysed using the advanced available techniques for examining the seepage potential of the dam. This will help to mitigate the chances of seepage in the dam and to install the remedial measures for seepage prevention. Also, Diamer Basha dam whose seepage potential is to be determined here, is up till now the highest RCC gravity dam in the world having height of 272 m. The dam safety and stability will be at stake, if there are chances of seepage in the dam either in RCC dam body or its foundation or at the dam body/foundation interface. Through taking into account these technical considerations of safety, stability and economy associated with the dam structure; numerical analysis of seepage of dam geometrical section is necessary to be done. In this research, numerical analysis of Diamer Basha dam will be done for seepage, using the technique of finite element modelling in Geo-Studio software (SEEP/W) to obtain best results. In later stages, obtained results will be used to evaluate the relevance of sseepage potential on the dam's on-going construction and its safety and stability.

Through the displacement analysis, the reaction of the dam body and its foundation will be analysed, how they will behave under the action of the applied loads in the given conditions. The stress analysis will be done by using SIGMA/W and this will help to determine whether stress produced within the dam body are within prescribed limits or beyond the bearing capacity of material of dam body. The value of the stresses, if more than the allowable limits, will cause crushing of the materials. The value of displacements will make it possible to know how much settlement will take place. The possibility of higher displacement values will make the whole dam vulnerable, might lead to the catastrophic situation. The installation of safety measures such as grout curtains will also be analysed here. It is also needed to know the change in stress or displacement values within the dam body, upon installation of safety measures at various locations along the RCC-foundation interface. Hence, stress analysis of the Diamer Basha dam is also necessary for the structural safety and stability.

The research is useful as limited work is available on seepage and stress analysis of RCC dams in the literature. Application of RCC dam's technology is getting common throughout the world because they are more economical and have faster construction pace than the traditional earthen dams or zoned dams but comprehension of its design features and geometrical components involve complications, as it is latest technology in the field of gravity dams. In Pakistan, similar trend is followed and new dams such as Dasu dam are constructed using RCC technology.But challenge faced here is that the theoretical basis of design is not firmly established yet now as it requires consideration of different geotechnical features of different dam sites and research is required to be done in this arena. The comprehension of seepage patterns and deformations in RCC dams also requires analysis of features of different materials which are part of geometry of dam' body. In addition, this work may provide some useful suggestions for consultants involved in the construction of Diamer Basha dam design. The impact of different materials and their properties upon the seepage patterns along with deformations in different parts of the dam body is also to be analyzed and vulnerable parts will be discussed at details to render basis for additional research. For design of other RCC dams, this study is helpful to understand the seepage patterns within the dam body and foundation.

This study is quite useful in the context of Pakistan as the project is under execution and the proposed guidelines will help the industry practitioners to replicate the results of this study. It is easily possible to understand the seepage paths, pore water pressure and water total head profiles within the dam body or its foundation bed for the new dams. The installment of monitoring devices do not give the exact values of seepage or deformations at different locations in the dam body but usage of FEM will make it possible to have exact values of seepage and deformations across the dam section. In operational phase of dam, it is also possible to compare these numerical analysis basedresults with the monitoring devices' results, because piezometers will be installed to detect any water leakage after the post-construction stages. This will help to establish sound relationship between the observed patterns and the numerical results, to have sound basis and develop the research trend in the emerging field of RCC dams.

1.3. Problem statement:

As the seepage and stress constitutes two important analysis of the dam and their importance is based on the fact that seepage phenomenon or undesirable stresses and displacements, makes the dam potentially vulnerable in terms of safety and stability; hence it is necessary to do the seepagee and stress analysis of not only the dam body but also the dam body-foundation interface and the foundation, for the different conditions of loading and water level conditions. The seepage though the foundation assumes more significance as it may cause differential settlement or undesirable effects disturbing the whole dam structure and putting the whole functioning of the dam at stake. Also, the greater displacements in different parts of the dam specifically the RCC-foundation interface, might impact the dam' structural stability. The proper analysis of the dam's seepage potential and stresses and displacements is now done through numerical techniques and (SEEP/W, SIGMA/W) arethe programs used for seepage and stress analysis, for different water level conditions. In this study, Diamer Basha dam, which is a Roller Compacted Concrete gravity dam, lying on rock foundation, will be analysed for its seepage and stress potential.As the project is under execution and dam geometry is yet to be made; hence, it is very important to analyse it under different reservoir water levels, for uupstream and ddownstream of dam.

1.4. Objectives:

The objectives of this study are as follows,

"To investigate the seepage potential of Diamer Basha dam and evaluation of the dam's stability criteria for practical application".

1.5. Contents of the thesis:

Chapter.1: This chapter describes the precise summary of the research work.

Chapter.2: This chapter reports literature review, highlighting the factors causing seepage and impacts of deformations upon stability, supported by case studies about RCC gravity dams.

Chapter. 3: This chapter discusses the research methodology, followed to achieve the set objectives of the research work.

Chapter. 4: This chapter reports the results and discussions because of finite element analysis.

Chapter. 5: This chapter summarizes the conclusions and few key recommendations, obtained from the study.

Chapter. 6: This chapter reports the references related to the thesis.

Chapter # 2

2. Literature review

2.1. Dam:

A dam is a hydraulic structure, constructed across a water channel for water pondage; and is used for various purposes, such as flood control, irrigation, navigation, and sedimentation control and hydropower generation. There are different types of dam when described in structural aspects such as an embankment dam (earthen, rock or combination of the two), buttress dam, gravity dam, and arch dam. When considering embankment dams, they are of two typesnamely homogeneous embankments and zoned embankments. Dam failure occurs because of variety of reasons such as leakage and piping, overtopping, spillway erosion, excessive deformation, sliding, gate failure, faulty construction and earthquake instability.

2.1.1. Seepage phenomenon in a dam body:

Seepage is the downward movement of water into the soil subsurface strata from a reservoir. It is the most critical phenomenon taken into account while planning and designing of a dam.RCC dams are vulnerable to seepage through horizontal lifts, vertical contraction joints or cracks which ultimately reduces tensile and shear strength (Banthia, 1992). Also, 35% of the earthen dams failed due to seepage (Omofunmi, 2017). Seepage is the reason of failure of 20% of gravity dams (Yao and Liu, 2021). Different factors such as degree of compaction, mixture proportioning, placement method and bedding mortar on the lift surfaces influence the permeability of RCC structure.

2.1.2. Stress and displacement analysis for concrete gravity dam:

Stress and displacement analysis make it possible to have values of different types of stresses and displacement at various locations within the dam body including its foundation. Numerical modelling technique is recommended to be used for stress analysis to analyze the complex deformation behaviour of concrete gravity dams, so that the dam deformation response, under the influence of known loading and thermal conditions can be significantly established (Graham, 1999); (Cruess, 2014). Deformation behaviour is the key index to evaluate the health state for long-term service of concrete dam structures; and is important to know as it varies under the impact of external loads because geographic conditions, material properties and ambient conditions are not the same for each dam (Ratnayaka, 2009).

Diamer Basha dam is Roller Compacted Concrete (RCC) gravity dam, which is selected as a case study to examine its stability for seepage and stress analysis. The dam is located on Indus River at Diamer, 40 km downstream of Chilas district, KPK Pakistan.The objectives of the dam are manifold as it is primarily constructed for water storage water storage capacity of 6.4 MAF and hydropower potential of 4500 MW, too. It is the tallest RCC gravity dam in the world so far with 272 m height, so its planning, design and construction need special considerations (Ali, 2020).

Table 2.1 Key features of Diamer Basha dam highlights the key features of the dam.

Table 2.1 Key features of Diamer Basha dam

Dam type	Roller Compacted Concrete
Height of dam	272 m
Spillways	14 bays (11.5m x 16.24m)
Gross storage	8.1 MAF (10 BCM)
Live storage	6.4 MAF (7.9 BCM)
Installed capacity	4500 MW (12,each turbine of 375 MW)
Annual energy	18,097 GWH
Lowest foundation level	898.0 m asl
Normal minimum operating level	1060.0 m asl
Normal maximum operating level	1160.0 m asl
Elevation of dam crest	1170.0 m asl
Volume of RCC	16,752,500 m^3
Execution by	WAPDA
Consultant	M/s Diamer Basha Consultants Group
Contractor	M/s Power China-FWO JV
Commencement date	August 2020
Completion Date	February 2029

Source: www.wapda.gov.pk

Figure 2.1shows the location map of dam site.

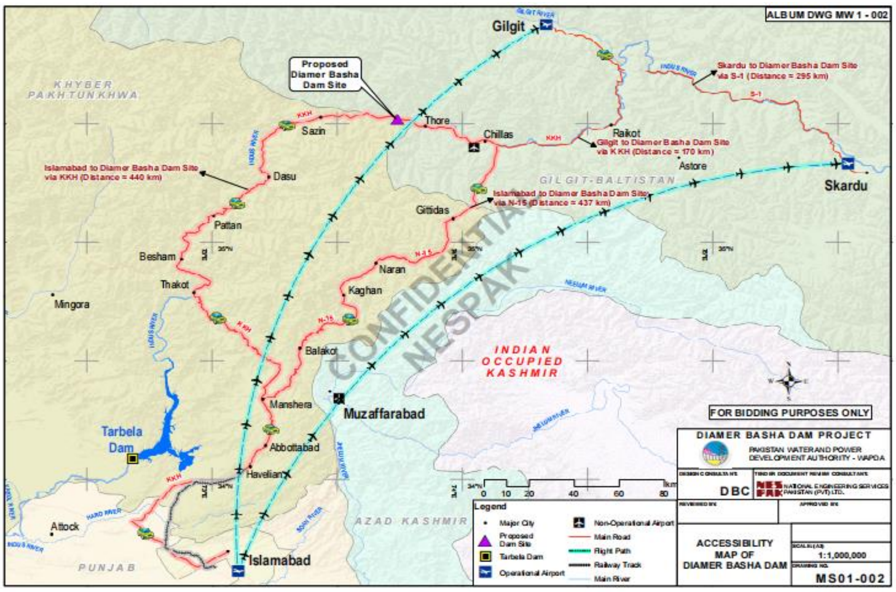


Figure 2.1: Location map of Diamer Basha Dam

2.2. Dam characteristics:

Diamer Basha Dam is an RCC gravity dam with slightly curved in elevation, lying on the rock foundation. Total length of the dam along crest level is 1169 m and 5 reservoir flushing outlets are provided at the lower level of the dam body for the purpose of sediment flushing. There are 36 separate blocks in the RCC dam body, with abutment blocks at both ends of the curved crest. The dam x-section has a width of about 220 m at U/S and D/S including the abutments. Upstream facing of the dam body is 1.5 m wide, composed of reinforced cement concrete having double metal water stops at vertical block joints for controlling seepage. Grout-enriched Roller Compacted Concrete having width of 0.5 m is also placed with reinforced cement concrete. (Ali, 2020). The dam section along longitudinal axis is shown in the Figure 2.2,

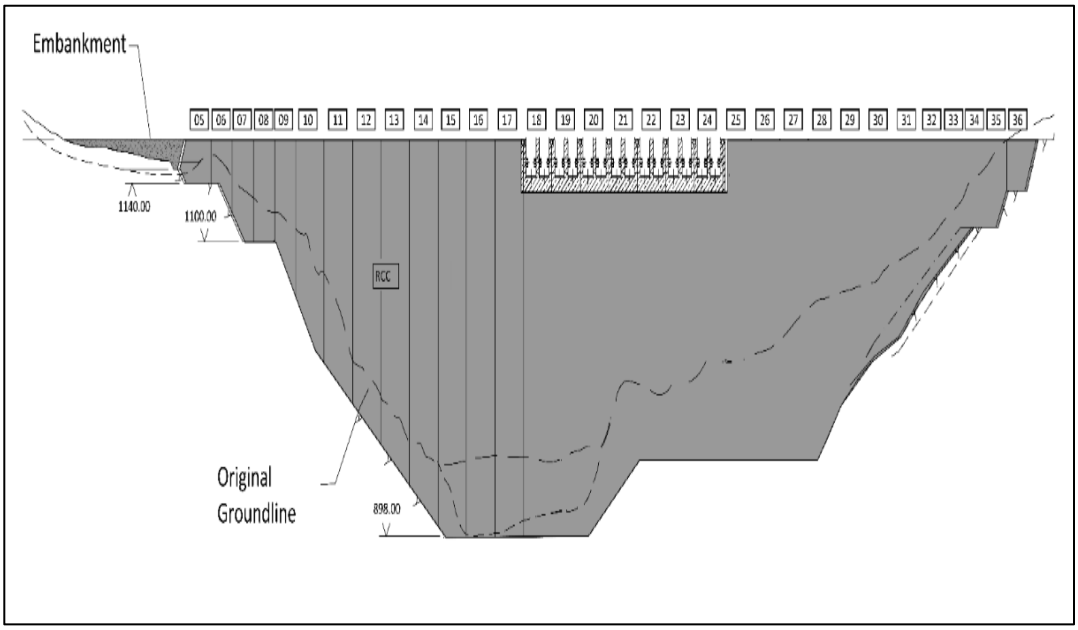


Figure 2.2: Longitudinal section along dam crest axis

The operational head of the dam varies between 1060 m and 1160 m with flood level of 1167.7 m from sea level. The foundation level of the structure is sitting on 898 m from the sea level.

2.3. Foundation bedrock characteristics:

Diamer Basha dam site is underlain by bedrock of the Chilas Complex, comprising gabbronorite and ultramafic rock intersected by doleritic dikes and pegmatite veins. Overburden consists of river and nullah deposits in form of terraces and alluvial fans, locally extensive moraine sediments, and slope debris from rock toppling and sliding. The rock outcrops cover about 26% of reservoir area and mainly comprise norite. Poisson's ratio of the intact rock is 0.206 and young modulus of deformation is 77.2 GPa (Ali, 2020).

2.4. Theoretical basis for seepage and stress analysis:

Darcy's law is used for the computation of seepage through both saturated and unsaturated soil. Darcy law states that,

$$q = ki \qquad \text{(Eq -1)}$$

Where, q is the specific discharge, k is the hydraulic conductivity and i is the gradient of total hydraulic head. SEEP/W is generally used to simulate the seepage conditions in saturated and unsaturated conditions, following the Darcy's law. Another form of Darcy's law is,

$$v = ki \qquad \text{(Eq -2)}$$

In Eq – 2, v is the Darcian velocity.

Numerical analysis software SEEP/W computes the Darcian velocity, not the actual average velocity that can be obtained by dividing the Darcian velocity by the porosity of the soil. (Geo-slope, 2018)

The finite element equation used in the SIGMA/W formulation for a given time increment is

$$\int_{v}[B]^{T}[C][B]dv\,\{a\} = b\int_{V} < N >^{T} dv \, + \, p < N >^{T} dA \, + \, \{F_n\} \qquad \text{(Eq -3)}$$

Where, [B] = strain-displacement matrix, [C] = constitutive matrix, {a} = column vector of nodal incremental x- and y-displacements, < N> = row vector of interpolating functions, A = area along the boundary of an element, v = volume of an element, b = unit body force intensity, p = incremental surface pressure, and $\{F_N\}$ = concentrated nodal incremental loads (Geo-slope, 2018).

2.5. Methods for seepage analysis of dams:

There are various methods employed for estimation of seepage through dam body and its foundation i.e., analytical methods, numerical methods and eexperimental methods/physical models.

2.5.1. Analytical methods of seepage analysis:

At present, different analytical equations are available to calculate seepage through the body of the dam i.e., Dupuit's solution, Casagrande's method, Schaffernak& Van Iterson method. However, these equations are usually used for earth-fill dams and give an approximation of seepage through the dam body. In addition, these methods are based on different assumptions for finding the quantity of seepage through the dam body.

2.5.2. Numerical methods for seepage calculation:

Analytical methods are usually used for simple geometries while for complex dam geometry such as RCC, numerical methods based on FEM are very useful and their accuracy depends on geometrical and material properties. In numerical analysis technique, scientific and technological problems are solved using computing technology which is capable to carry out the simulations more easily, smoothly and conveniently than the methods based on hand-calculations. In addition, analysis is more detailed and has less relative error in comparison with the data obtained from field observations. When using numerical modelling for seepage analysis, care should be taken for its proper application along with defining the constraints because it helps in the design process through key insights into potential seepage problems and various failure mechanisms.

2.5.3. Physical models for seepage calculation:

Physical models show the general behaviour of seepage through dams including phreatic line and water flow rate and are one of the pre-construction requirements for understanding the dam behaviour and verification of initial dam design. They are also good for the situations involving complex hydraulic conditions and irregular site-specific conditions.

2.6. Roller Compacted Concrete (RCC):

RCC is a type of concrete having similar composition as that of conventional concrete, with zero slump in its fresh state and is usually handled by vibrating drums and rollers (Habib, 2021). It has low maintenance requirements and is particularly good for pavements and hydraulic structures. Some properties of RCC, which makes its preferable for future usage, are rapid construction pace, good control over heat generation, suitability for massive concrete structures in different environmental conditions and durability at lower cost than conventional concrete (Habib, 2021). The compaction of RCC is achieved by external vibratory roller where the technique of ramming is combined with usage of external vibration (Banthia, 1992).

2.6.1. Seepage in RCC dam:

The most critical phenomenon to be taken into account when planning and designing dams is the seepage of water through and under the body of the dam. If seepage is allowed to occur and no maintenance is made, after a certain period, the dam breach may occur, failing the dam structure. The RCC failure is considered as one of the most catastrophic events and is defined as a collapse or movement of part of a dam or its foundation/ abutments so that this structure cannot retain water anymore.

In case of large RCC dams constructed on foundation bedrock, seepage is one of the important considerations in the design process as these dams have large reservoir volume and their maintenance is difficult. Permeability is important for seepage control and susceptibility to frost damage. For any concrete, two important factors, which affect its permeability, are entrapped air and porosity of hydrated cement matrix. The permeability of RCC is different from conventional vibratory concrete because of different mix proportioning and the technique of compaction used (rollers) (Banthia, 1992).

2.6.2. Factors affecting dam stability:

Main agent of seepage through the RCC dam body is water pressure and this can occur though foundation bed or through the interface between the dam body and the foundation. Although a minor seepage can be found within RCC dam body or the U/S face of RCC dam body, but in ordinary conditions, seepage through foundation bed or through the interface between the dam body and foundation is considered.

For the gravity dams lying on rock foundations, in normal conditions designers assume the plane of failure to be between dam and foundations. The RCC-bedrock interface is important for the strength and stability of the dam as it is one of the potential sites of crack initiation and propagation. It might be due to different material properties in the RCC dam body or the foundation.

As foundation seepage is concerned, it is critical as usual nature of bedrock foundation is complex and full comprehension of the foundation characteristics is not possible. Through numerical analysis, an approximation of seepage can be made. For this reason, it is necessary to know the seepage not only through dam body but also though the bedrock foundations, as it will help to mitigate any chances of seepage in the foundation bedrock.

Seepage behaviour helps us to know the uplift pressure at the base of the dam and this uplift pressure is contributing to the displacements of the dam’s body as external hydrostatic pressure acts on it. In addition, there is displacement and stress variation within the dam body and the foundation because of possible seepage. Because of this reason, stress and displacement variation is necessary to know by using SIGMA/W software.

2.7. Seepage through RCC dam body:

Seepage can occur through RCC dam body because of various factors such as thermal cracks, de-bonded joints, horizontal layered structure and construction method.

2.7.1. Thermal cracks:

Concrete gravity dams have usually large sizes, it is difficult to completely avoid the thermal cracks because of their large size, and these cracks in the RCC dam body constitute one of the major seepage water path at different locations. These thermal cracks make it possible to have the potential flow paths for seepage water in the dam body. Seepage phenomenon produces uplift pressure, thereby greatly affecting the stability and safety of the dams.

2.7.2. De-bonded joints:

The application of lift method of construction renders horizontal construction joints in the RCC dam body and these lifts are composed of various “fresh to fresh” compacted layers. Because of these de-bonded joints, there are chances of seepage phenomenon ultimately leading towards uplift pressure generation, putting the dam’s safety and stability at stake. When there is temperature variation in the cooling process of the dam body, tensile stresses will develop in zones near the dam body’ faces. If these stresses are more than the tensile strength of the RCC, there is possibility of occurrence of de-bonding effects. (Ali, 2020)

2.7.3. Horizontal layered structure:

RCC, being a layered structure, horizontal layers in RCC can be the possible seepage channel. Construction method also influences the permeability of RCC mass (Habib, 2021). Sloped layer method is used at Diamer Basha dam for RCC placement and this helps in controlling the thermal stresses (Ali, 2020).

2.7.4. Compaction method:

The permeability of RCC is higher than conventionally proportional and placed concrete and higher than conventionally mass concrete. When permeability of RCC and conventionally placed concretes are compared, RCC has smaller water-cement ratio but its compaction technique and mix proportioning cause it to have an internal structure through which water can easily flow (Habib, 2021).

2.7.5. Water-cement ratio:

The high water-cement ratio causes an increase in large diameter capillary pores, which helps in the flow of liquid giving rise to high value of coefficient of permeability. Following the same trend of high water-cement ratio helps in achieving good compaction by rollers and lower value of coefficient of permeability. No specific criteria can be established regarding high water-cement ratio in the RCC (Al Baghdadi and Khan, 2018); (Habib, 2021).

2.7.6. Hydraulic conductivity

Hydraulic conductivity of RCC is a measure of the relative ease with which RCC will transmit water under a hydraulic gradient. For laboratory measurement of hydraulic conductivity, different methods are used such as steady constant-head test, transient constant-head test, transient pulse test, constant-flow test, falling-head test, and flexible wall permeameter. These methods are generally used for 1D laminar flow of water within porous material such as RCC. These tests may not be real indicator of field conditions because small test specimens may show different flow patterns than instruments used in the actual field due to existence of heterogeneous conditions at the field (Zafar, 1997).

2.8. Factors affecting rock foundation permeability:

Permeability of a rock can be defined as, “The measurement of the ease with which fluids can travel through a medium under the influence of driving forces”. For representation of seepage though rock bed, co-efficient of permeability is used.

2.8.1. Co-efficient of permeability:

Darcy’s coefficient or engineer’s coefficient is usually considered as coefficient of permeability. It can be defined as,” the discharge velocity through a unit area under a unit hydraulic gradient”. Darcy’s coefficient depends upon properties of fluid such as viscosity and density of fluid as well as properties of medium. Flow characteristics in a rock mass are defined using the approach of continuum approximation, dis-continuum approximations and laws defining the groundwater velocity.

There are different methods used for the determination of rock mass permeability. For laboratory determination, permeability tests are model tests, individual fissure tests, representative sample tests, and evaluation of methods of analysis. Rock mass permeability is used for assessment of ground water movement. In addition, this constitutes an important part of design of hydraulic structures. Seepage patterns can develop in the foundation bedrock after reservoir filling. They are used to judge the safety measures adopted against seepage potential, sources and exit point of seepage design of remedial measures against seepage (USACE, 1986).

2.9. Case studies:

1. Zafar (1997) analyzed the unusual conditions encountered in the construction of Tarbela dam. In 1974, RCC was also used in Tarbela dam to replace the soil and embankment when collapse of one of the 45 ft outlet tunnel occurred during initial filling. A large volume of RCC, more than 3.3 million yd^3 was used for replacement. They concluded that large gravity dams can be easily constructed using RCC with rapid pace of construction.

2. Banthia (1992) showed that permeability depends upon interconnected compaction voids and the usage of Silica fume in the RCC gradually the permeability of RCC.
3. Portella (2018) discussed the physicochemical seepage water analysis of Jordao river dispersion, which is an RCC dam having height of 95m in Brazil. The study reported that this analysis is a good indicator of identification and evaluation of quantities of solid materials as they are leached out from RCC Jordao river dispersion structure; further added that the seepage is gradually conforming to the reservoir conditions to reach stability.
4. Soares (2018) discussed the crack propagation in different sections and precautionary measures taken in the Salto Caxias hydroelectric project of Brazil, which is an RCC gravity dam having height of 67 m along with dam's foundation of basaltic rocks. They analyzed that concentration of largest infiltration was on the riverbed and there was no damage caused by the seepage through the cracks as the treatment was well applied.
5. Kamanbedast and Delvari (2012) have studied the rate of seepage through Maroondam using FEM based software i.e., Ansys and Geo-studio. Seepage rate obtained from both software under different conditions are compared. It is concluded that seepage rate given by Ansys was 18 percent less than the Geo-studio. This difference may be because of different method of analysis. Stability analysis of the two programs was also compared and it was deduced that results given by Ansys are more reliable. Dam was found to be in safe operational conditions according to software results.
6. Imran and Babar (2014) have studied the quantity of seepage through Hub Dam by using SEEP/W program. Original dam body is composed of three different kinds of reaches but only one reach with the core wall is simulated by using SEEP/W program. Seepage analysis was carried out for different reservoir levels i.e., maximum, normal and minimum pool level. Validation of the SEEP/W model was made by comparing the simulated results against the observed ones. The dam was safe under different working conditions. It was concluded that

SEEP/W model could be safely used to evaluate seepage through the dam body. This study has approved the applicability of SEEP/W for the seepage evaluation.

7. Bochnak and Saracco (2020) did numerical analysis of Longtan dam by using Geostudio. From the seepage analysis done, peak seepage velocities in the dam foundation were within allowable range and dam was found safe against seepage danger. From the stress analysis, little stress values (0-2 MPa) were found in the dam body. Nevertheless, high compressive stresss of 12 MPa was present at dam toe and tensile stress of 16 MPa was found at dam heel. Due to the possibility of tensile failure at the dam heel, it was recommended to reinforce the dam heel.

8. Yao and Liu (2021) conducted a research project on Sl dam (China) having height of 117 m and length of dam crest is 310 m. They monitored and analyzed the seepage of different sections of the project, which include right and left banks, concrete gravity dam body and its foundation. The monitoring was made for regular operational stage and anti-seepage system (grout curtain) was found to be giving good safety against the seepage condition at the dam and the foundation. In addition, analysis of uplift pressures and seepage pressure around the dam were made along with the observation taken for measuring weir of Sl hydropower station dam. It is stated that, from the recorded and analyzed data of uplift pressure, seepage flow, seepage pressure of dam foundation and seepage around the dam and its changes; all are found to be in normal conditions and seepage condition of the gravity dam is also in a safe state.

9. Zhang et al. (2021) analyzed that a large number of concrete dams have been failed because of the failure of foundation strata. Failure of the Austin dam on the Colorado River occurred in 1900 due to development of cavities in its limestone foundation. In another case study done in 1928, a concrete gravity dam in California, St. Francis dam having height of 205 ft failed when conglomerate in one abutment weakened due to exposure to moisture from the reservoir.

10. Zhang et al. (2021) discussed that importance of seepage of foundation bedrock for the dam’s safety can be judged from the fact that in 1959, large-scale geological investigations were made on Malpasset Arch dam having 200 ft height

but it failed because of the presence of a clay seam in the rock at one of its abutment.

11. Zhang et al. (2021) analyzed that seepage characteristics of the dam are vulnerable to be affected by Calcium leaching phenomenon. Leaching of Calcium ions in the aqueous environment of concrete increases the porosity and permeability of material and material nature is greatly affected. This causes the seepage characteristics of concrete to constantly evolve. The impoundment of Fengman concrete gravity dam was started in 1942 but after 80 years the concrete deterioration and leakage problems happened in the dam because of calcium leaching effect.
12. Zhang et al. (2021) discussed the impounding of the Gutianxi flat slab buttress dam, which was started in 1961. In 2000, serious leakage problem occurred in 8 sections of the dam and calcium leaching occurred in 20 sections of the dam, causing concrete strength to be reduced from 49.6 MPa to 37.9 MPa. This again shows that in long-term operations, calcium-leaching phenomenon affects the diffusivity, permeability and strength evolution of cement based materials. Hence, due to evolving seepage characteristics of the concrete, it is necessary to analyze the seepage of RCC gravity dams along with taking precautionary measures for preventing the calcium leaching effects.
13. Liu et al. (2003); Liu, Feng, and Ding (2003) did the FE analyses of Three Georges dam, using the numerical modelling and stability analyses for the single most critical powerhouse dam section, and showed that both horizontal and vertical displacements in the heel, toe of the dam and top from the planar model are larger than the same parameters from the 3D model which is due to difference in boundary conditions.
14. Ratnayaka (2009) suggested that numerical modelling helps to know the uplift pressure, present at the base of concrete gravity dams, as it is important for the anti-overturning stability of the concrete gravity dams because of their wider base. It varies from the dam heel to the dam toe and its measurement is recommended.

15. Ratnayaka (2009) depicted that numerical simulation of the dam’s deformation behaviour gives the sound way to understand the effects of different external loads. In addition, for the determination of structural displacement, hydrostatic pressure is more important than uplift pressure where thermal effects dominate the displacement at the dam crown, whereas with the decrease of elevation, the water level dominates the effect. In addition, the data obtained and collected using various instruments is important for health monitoring of concrete dams, which helps to comprehend the dam behaviour and is important for these dams in high service years. The monitoring data cannot depict the information that how the change in water level affects the dam deformation. These observations stress a need to do the numerical.
16. Ratnayaka (2009)analyzed that hydro-static pressure at the U/S face is decisive to know the displacement response of the dam due to water level variation and the uplift pressure at the dam base is of negligible significance, also, the foundation part and the body of the dam should be analyzed together in the simulation.

Chapter 3:

3. Materials used and methods employed

3.1. General introduction:

The study focusses on seepage through Diamer Basha dam resting on bedrock foundation by using the technique of numerical analysis based on finite element modelling, in Geo-studio. This section reports the specifications of Diamer Basha dam under consideration and procedure used for the numerical simulations in SEEP/W and SIGMA/W program of Geostudio (2018 R). SEEP/W and SIGMA/W are the finite element soft wares used to analyze the RCC dam model for seepage and stress calculations alternatively. This chapter covers the methodology used for achieving all the objectives of this study.

- ◆ Complete understanding of the existing site conditions.
- ◆ Data collection from WAPDA.
- ◆ For seepage calculations, identification of seepage conditions in practice that may cause dam failure.
- ➢ Frequent conditions (Steady state condition, during operational condition)
- ➢ Less frequent conditions (Rapid reservoir drawdown condition, post construction stage).
- ◆ For stress calculations, following conditions are used.
- ➢ Normal working conditions (minimum water level, maximum water level)
- ◆ Incorporation of the inputs in dam model in computer soft wares (SEEP/W, SIGMA/W) followed by modelling and simulation of the model.
- ◆ Discussion of the outputs obtained from the analysed model.

The dam geometry is analyzed for minimum normal operating level, maximum normal operating level, safety check flood level for steady state and post construction stage. Also, rapid draw-down condition is used in the analysis because of the probability of generation of excess pore water pressure due to rapid change in water level but in usual cases, phreatic surface does not change rapidly.

3.2. Numerical modelling in Geo-studio (SEEP/W, SIGMA/W):

Finite element modelling was use for seepage and stress analysis of Diamer Basha dam due to its complex geometry. Laboratory testing of RCC for seepage analysis requires sophisticated technology. Although, physical models are used to verify the dam model but numerical analysis is a better tool to deal with the materials like RCC and foundation bedrock. The calculations performed in SEEP/W are based on Darcy's law and stress analysis is based on FEM equation. Case study of Longtan dam (RCC gravity dam in China) is used as a reference case study.

3.3. Post construction stage analysis in SEEP/W:

Post construction stage analysis was performed for different water levels on U/S (160:267.7 m) and D/S water level is 0 m. The whole procedure for steady state seepage and post construction stage is same and only the D/S boundary condition is different, which is water total head having value of 0 m on D/S.

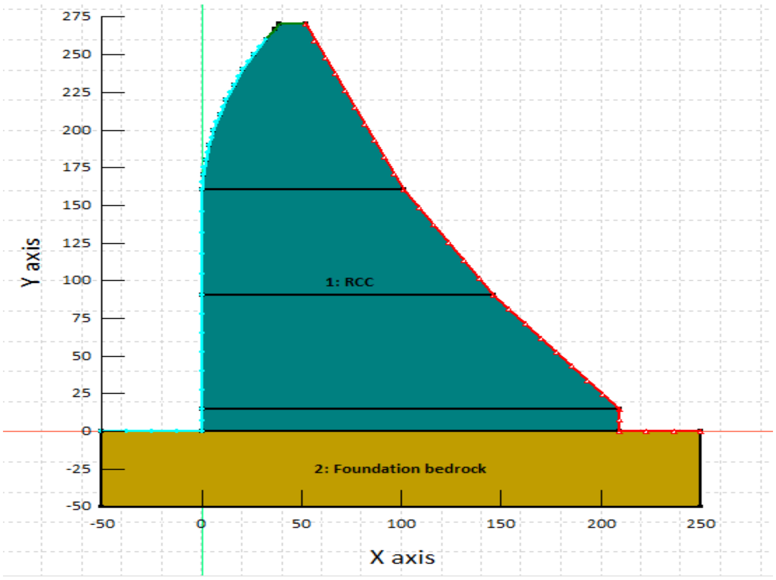


Figure 3.1: U/S water level (267.7 m), D/S water level (0 m)

3.4. Rapid draw down analysis in SEEP/W:

In rapid draw down analysis, water total head on U/S varies for different operational reservoir levels (160:260 m). Water is drawn at uniform rate in 10 days. Here, boundary conditions are different from the cases of post construction stage and steady state seepage. Potential face seepage condition is assigned on U/S face and water total head is assigned on D/S face, having value of 160 m. Rest of the whole analysis procedure is the same as steady state seepage analysis.

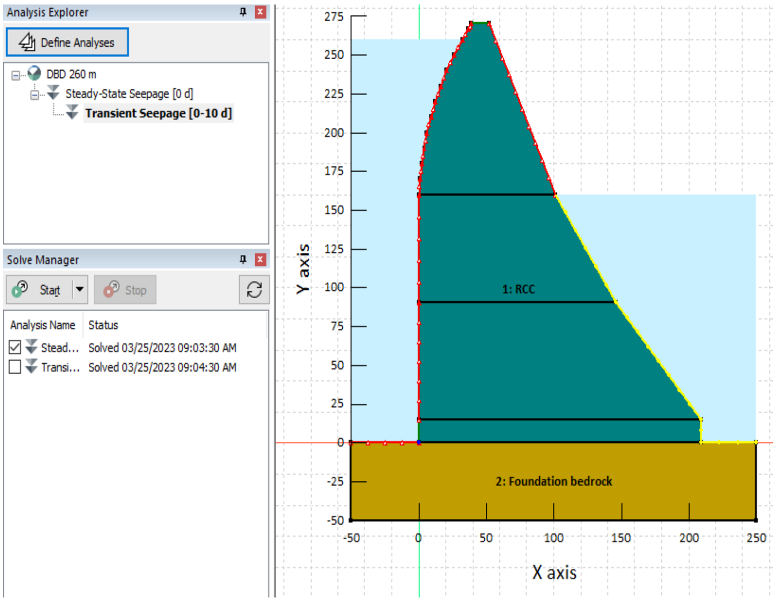


Figure 3.2: U/S water level (267.7 m), D/S water level 0 m

3.5. Steady state seepage analysis in SEEP/W:

Steady state seepage analysis was performed for different water levels on U/S (260:267.7 m) and D/S (15,90,160 m) using the SEEP/W software. The complete procedure for the analysis of a dam model in SEEP/W software for seepage calculation is described in this section. The following points are studied in the seepage analysis using SEEP/W; pore-water pressure, seepage quantity (for all the parts of dam body including foundation).

3.5.1. Creating problem workspace and defining analysis properties:

For creating SEEP/W analysis and setting of workspace, steady-state analysis is chosen, initial pore-water pressure conditions and convergence criteria are defined. Figure 3.3 and Figure 3.4 are showing the unit settings and sketching axes for the dam geometry.

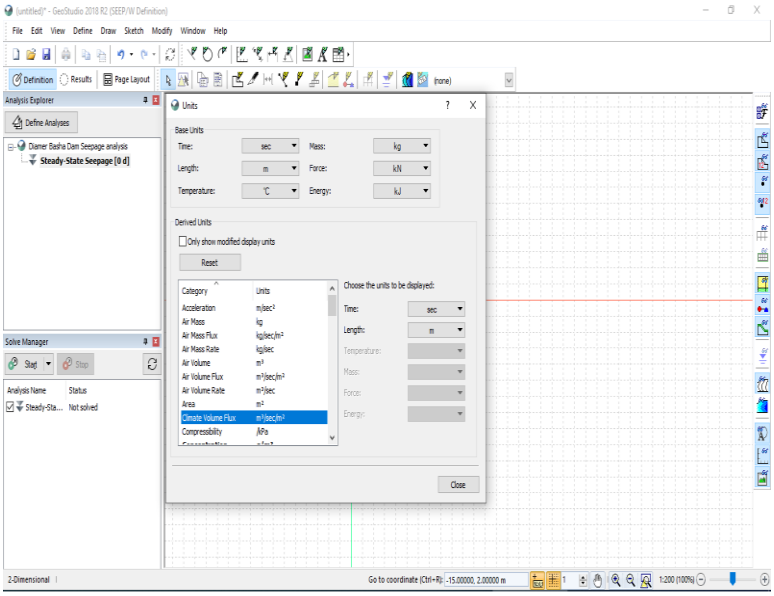


Figure 3.3: Unit settings for SEEP/W

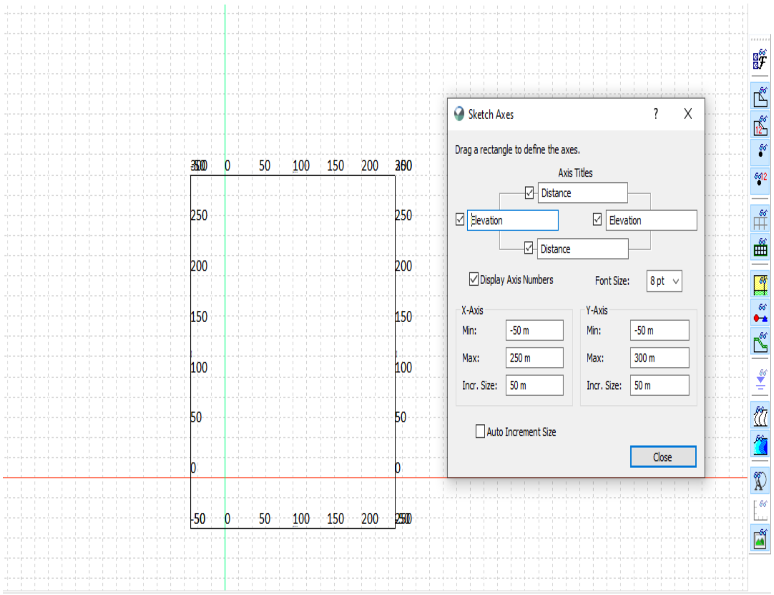


Figure 3.4: Sketching axes in SEEP/W

3.5.2. Drawing domain regions:

The regions in the domains can be drawn using CAD-like drawing tools such as drawing polygons and direct entry of co-ordinates using keyboard. Regions are shown in the Figure 3.5

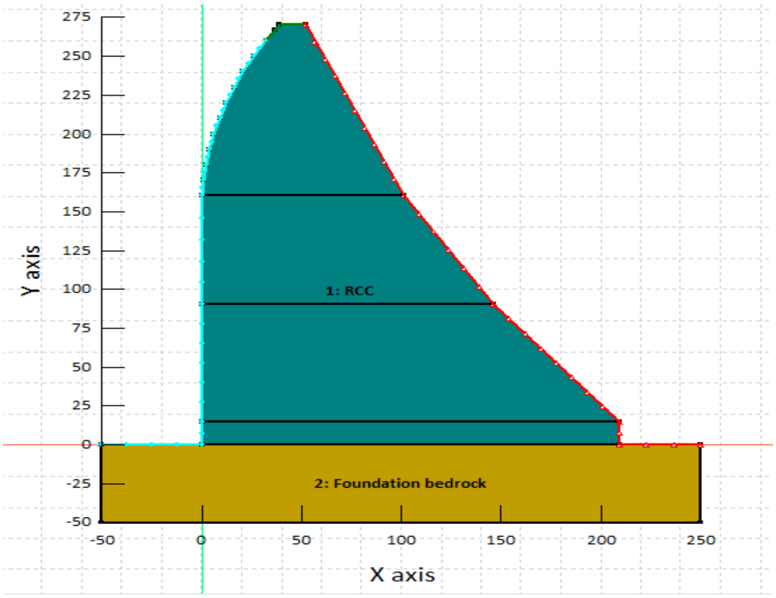


Figure 3.5: Regions of Diamer Basha dam

3.5.3. Defining and assigning material properties and pore-water pressure:

The material properties for seepage analysis are defined and applied to regions as mentioned in the table below.

Table 3.1 Material properties used in the seepage analysis

S. no/-	**Material name/type**	**Material behaviour**	**Hydraulic conductivity K_{hx}(m/s)**	**References**
1	RCC	Saturated	$2.7e^{-12}$	(Bochnak and Saracco 2020)
2	Bedrock foundation (Gabbro)	Saturated	$1.0e^{-7}$	(Ali et al. 2020)

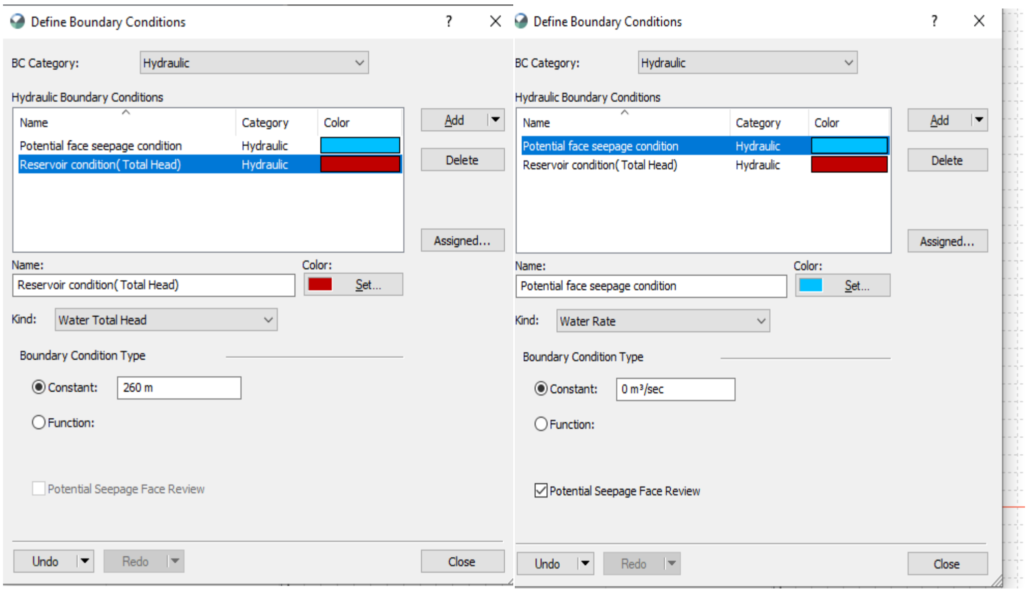
Initial pore-water pressure conditions are defined as follows.

Table 3.2 Water level for different working conditions

Min. normal water level	1060.0 m asl
Max. normal water level	1160.0 m asl
Safety check flood level	1167.7 m asl

3.5.4. Defining and assigning hydraulic boundary conditions:

Hydraulic boundary conditions are defined to simulate different conditions of pressure head, total head, pore-water pressure, unit flux (q) or total flux (Q). Total head boundary condition is applied on upstream and potential seepage face condition is applied on downstream of dam cross-section.



(a) (b)

Figure 3.6: (a) Total head boundary condition, (b) potential face seepage condition

3.5.5. Drawing mesh properties:

Mesh properties are drawn to refine the mesh for specific sections, boundaries or points and usually used for the entire domain.

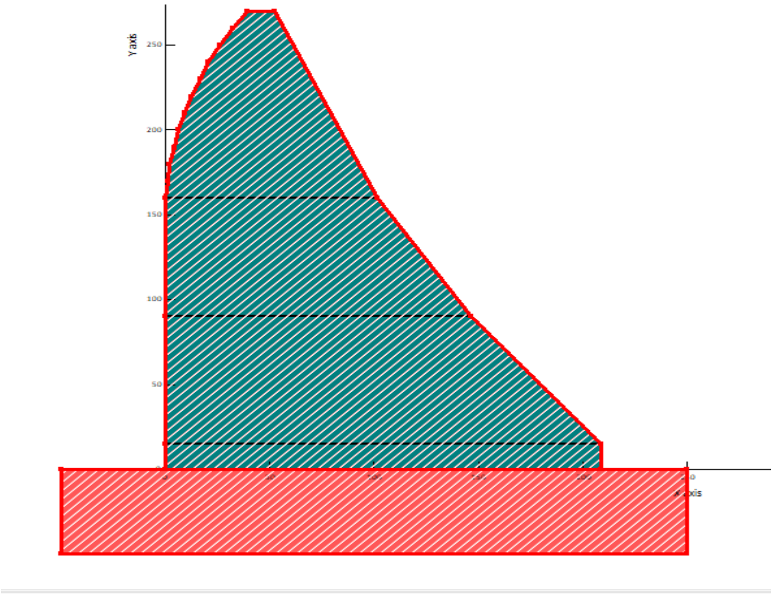


Figure 3.7: Meshing of dam cross-section

3.5.6. Analysis of model:

After completely defining the problem, analysis can be started using solve manager window.

3.5.7. SEEP/W model result:

Here, is a pore water pressure profile obtained through steady state seepage analysis.

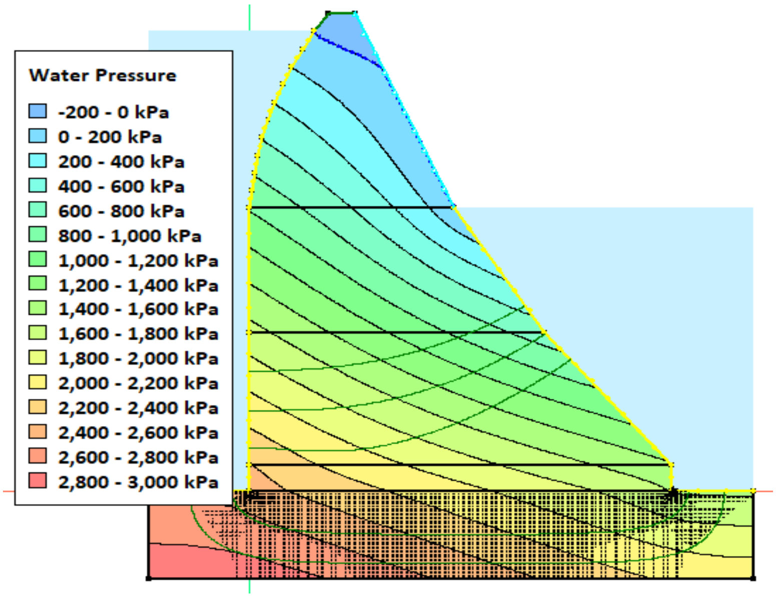


Figure 3.8: Steady state seepage analysis result

3.6. Methodology:

SEEP/W and SIGMA/W of Geostudio software were employed for seepage and stress analysis of the dam. First step involved in the modelling process involved is to set the seepage conditions, i.e., steady seepage or transient state condition, followed by the setting up of units and scale for the analysis. The units were taken as default units (SI units) and scale is taken as 1:200 for X and 1:475 for Y. From the Sketch tab, the extents (limits) of X and Y co-ordinates are defined. Breadth of the dam geometry is 209 m and height of dam geometry is 272 m. Coordinates are taken from the table given along the figure of the dam geometry, in the drawing file. Thus, the limits of X-axis is taken as [-50 m, 275 m] and the limits of Y-axis is taken as [-50 m, 300m] to take into account the dimensions of both the RCC dam body and the foundation. For drawing regions, first co-ordinates are entered using "Define tab" to obtain different points and then from "Draw tab", these points are used to made regions. Polygon region is selected by default. Next step is defining the materials and assigning them to the regions. The material properties for seepage analysis are defined and applied to regions. The foundation bed is composed of Gabbro rock with saturated hydraulic conductivity of $1e^{-7}$ m/sec. The saturated k of $2.7e^{-12}$ m/sec was used for RCC as reported in (Bochnak, 2020). From the Define tab, initial pore water pressure conditions were simulated for three conditions, (a) minimum water level (1060 m asl), (b) maximum water level (1160 m asl) and (c) safety check flood level (1167.7 m asl).

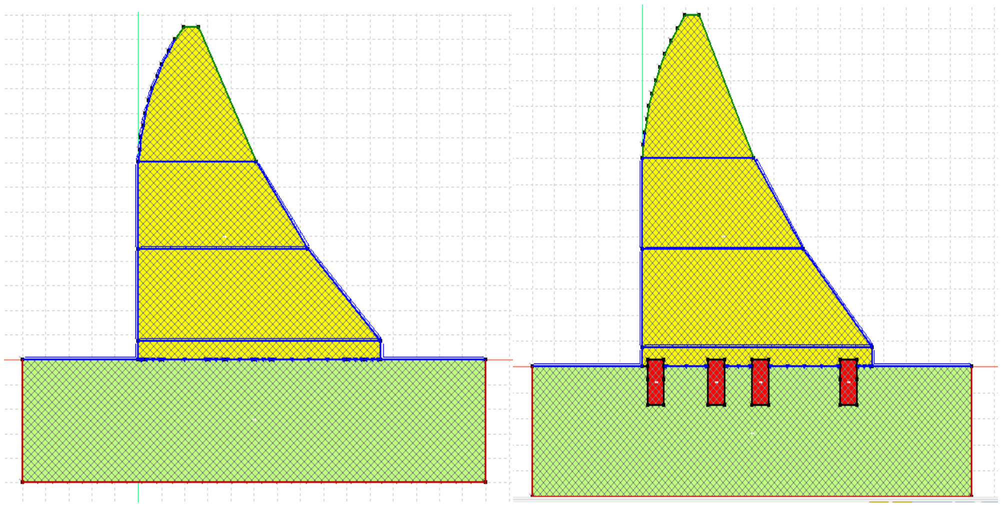
After assigning the materials, boundary conditions are defined. One of the boundary condition is water total head having values from 160:267.7 m. Second boundary condition is potential face seepage review, where water rate is taken as zero. For steady state and post construction stage, water total head is assigned on U/S of dam body and potential face seepage review is assigned on D/S of dam body. For rapid draw down condition, potential face seepage condition is assigned on U/S face and water total head having value of 160 m is assigned on D/S face. Here U/S water level varies from 160 m to 267.7 m and in the process of rapid draw down, water level be eventually brought to 0 m. The models for steady state and post construction stage are having different levels of water head at upstream (160:267.7 m) having consecutive intervals of 5 m and downstream face intervals are defined as (0, 15, and 90,160) m. Then meshing of the geometrical model is done followed by running the analysis. After analysis is done, results are displayed on the GUI (Graphical User Interface). From the results, pore water pressure, seepage velocities and different relevant parameters are obtained. After development of initial model, about 110 models are made where 66 models are made for steady state conditions, 22 are for post construction stage and 22 are for rapid draw down conditions.

Table 3.3 Conditions used in the seepage and stress analysis.

Condition	**U/S water level (m)**	**D/S water level (m)**	**U/S water level variation interval (m)**	**D/S water level variation interval (m)**	**Total models for seepage analysis**	**Total models for stress analysis**
Steady state seepage	[160, 267.7]	15,90 ,160	5	Constant	66	21 models without grout curtains, 21 models with 1,2,3 and 4 grout curtains successivel y
Rapid draw down/ transient condition	0	[160, 267.7]	Constant	5	22	No model
Post construction stage	[160, 267.7]	0	5	Constant	22	No model

3.7. Displacement analysis in SIGMA/W:

The SIGMA/W model in Geostudio is used for numerical analysis to estimate the stresses and deformations in the structure. The calculations in the SIGMA/W are used, being based on 2D plane strain theory. Same procedure is used for developing the model in SIGMA/W as for seepage analysis in SEEP/W analysis is used. For the analysis, linear-elastic theory is used. Positive stresses show compression while negative stresses show tension. Operational water level conditions are used for analysis. The material properties such as elastic stiffness and Poisson's ratio are of 20,000 MPa and 0.20 for RCC material respectively (Bochnak, 2020). For Gabbro rock foundation, the elastic stiffness and Poisson's ratio of 77,200 MPa and 0.206 respectively as specified in (Ali, 2020), were used to simulate the stress and displacement behaviour of dam body. During analysis, the base is restrained to move in the X and Y directions and the sides of the base are restrained in the X direction. The loads applied in the model are U/S hydrostatic pressure, D/S hydrostatic pressure, uplift pressure and self-weight. Initially no grout curtains are assumed to be part of the structure but because of larger displacements, a number of grout curtains ranging from 1-4 are alternatively assumed to be part of geometrical cross-section of Diamer Basha dam in other models and their effect is shown in the results.



(a) (b)

Figure 3.9: (a) Dam cross-section with no grout curtains and loads applied, (b) dam cross-section, with grout curtains.

Chapter # 4

4. Results and discussions

The result section deals with the variables obtained from the analysis of dam' geometrical section in SEEP/W and SIGMA/W. From the analysis done, different values of geometrical variables are obtained for different sections and locations in the dam. Different scenarios are discussed while considering the important parameter of quantity of seepage and pore water pressure at various locations, i.e., within the Roller Compacted Concrete dam body, at the dam body-foundation interface and within the foundation. Cases discussed are for the following water levels as mentioned in the table.

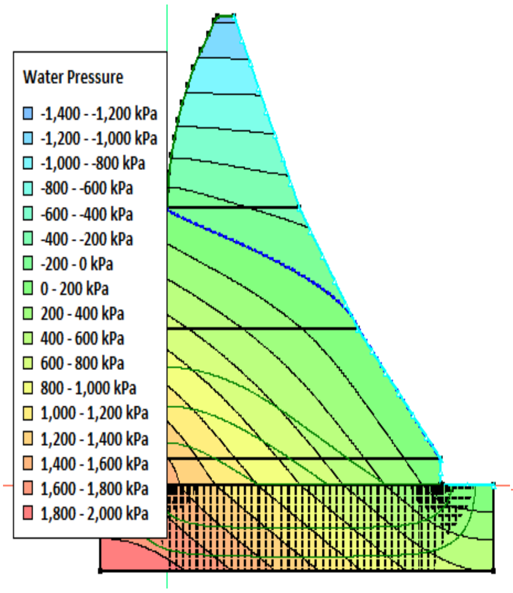
Table 4.1 Water level working conditions

Minimum normal water level	1060.0 m asl
Maximum normal water level	1160.0 m asl
Safety check flood level	1167.7 m asl

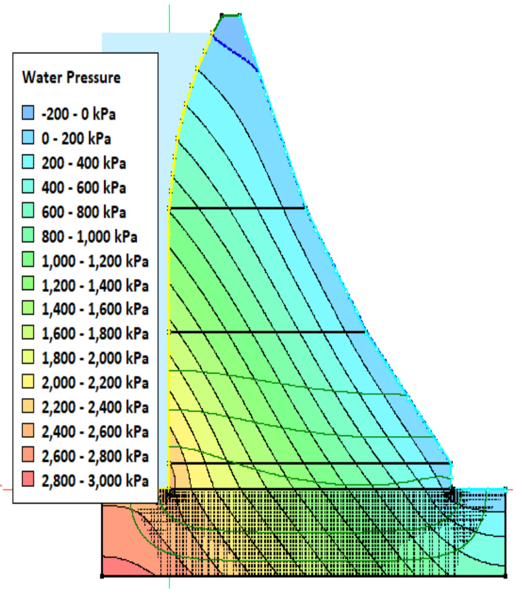
4.1. Seepage behaviour of dam body (post construction stage):

Here, water at U/S level is varying from 160m, 260 m to 267.7 m and at the D/S water level is at 0 m.

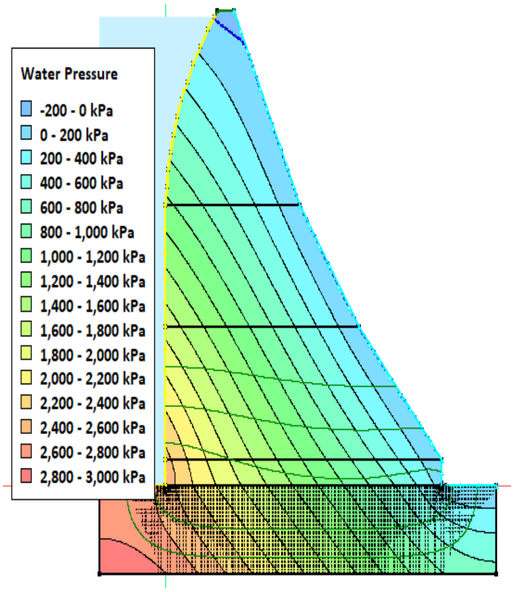
4.1.1. Pore water pressure profile:



(a)



(b)



(c)

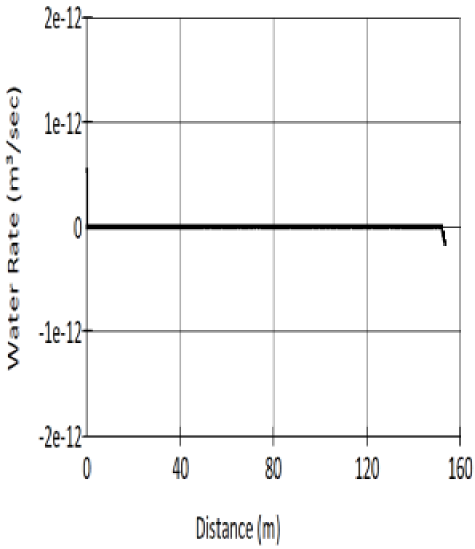
Figure 4.1: (a) Pore water pressure profile, U/S 160 m, D/S 0 m, (b) Pore water pressure profile, U/S 260 m, D/S 0 m. (c) Pore water pressure profile, U/sS 267.7 m, D/S 0 m.

Figure 4.1 (a) shows the pore water pressure profile for the U/S water head of 160 m and D/S water head of 0 m, which varies from -1400 kPa to 2000 kPa. The green lines are the flow paths at various points within the dam body and the foundation. As the water level on upstream decreases, so the pore water pressure within the RCC dam body and foundation decreases. This means, for the same dam body material, pore water pressure varies with the water level on the U/S and same trend is followed for the bedrock foundation. Figure 4.1 (b) depicts the pore water pressure for the U/S water head of 260 m and D/S water head of 0 m which varies from -200 kPa at top of the dam section (free board), within RCC and 3000 kPa at the left most edge of the dam foundation. This shows that pore water pressure depends on depth and as the depth increases, pore water pressure increases.Also, because of the homogeneity of the material in the dam body and the foundation bed,pore water pressure shows uniform variation. The broken lines show the seepage direction at toe and heel sections of the dam and they are the indication there is concentration of water at the toe and the heel section, due to which greater pore water pressure exists at the toe and the heel and these might be the vulnerable part of the structure but this is also an indication that pore water pressure can be mitigated by reinforcing the toe and the heel, instead of reinforcing the whole interface or the foundation.

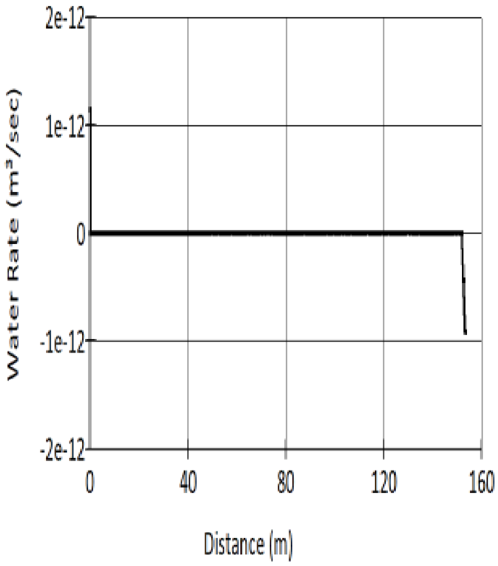
Figure 4.1 (c) shows the water pressure for the U/S water head of 267.7 m and D/S water head of 0 m. As in previous case, water level on U/S of dam is 260 m but here is 267.7 m. With the increase in depth, pore water pressure increases for both RCC dam body and foundation, but there is uniformity observed in values of pore water pressure for maximum water level (normal working conditions) and flood level conditions. From the comparison of three cases of post-construction stage in Figures (a-c), it is observed that negative pore water pressure or suction pressure has higher value in the case of minimal water level for working conditions. For the other two cases, positive pore water pressure is dominating in most of the RCC dam body and the foundation region.

4.1.2. Seepage quantity within RCC dam body:

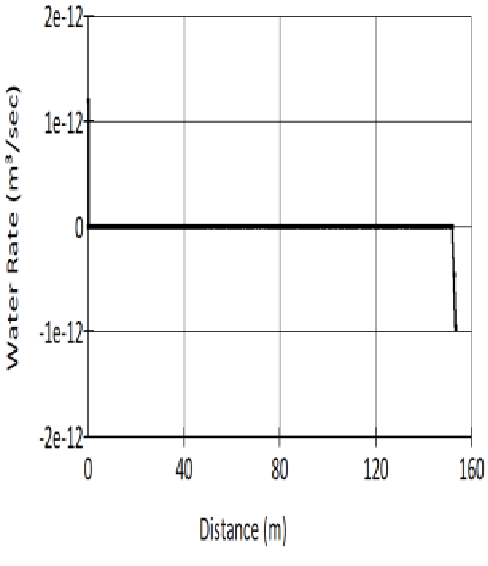
Seepage is the important parameter whose numerical value is of great significance for the safety of the dam structure. Its value, at any location within the dam structure shows the extent of water penetration and helps to install the seepage resistive or mitigativestructures. Within the RCC dam body, maximum value of seepage quantity is found at line lying at the middle of the RCC dam body as different values are found for different water head conditions at upstream and downstream.But, the maximum value is found within the middle of the RCC dam body. Hence, this section is chosen.



(a)



(b)



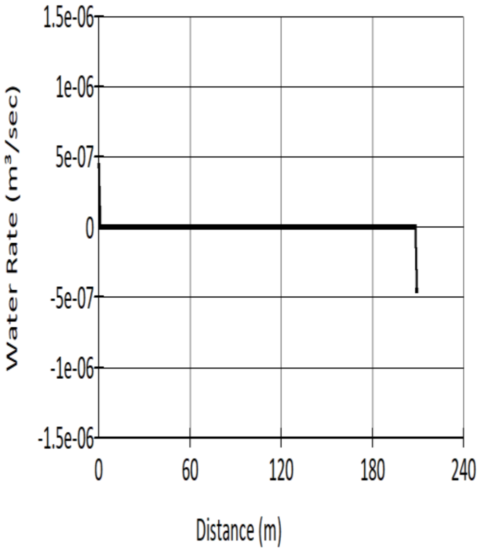
(c)

Figure 4.2: (a) Seepage quantity within RCC dam body, U/S 160 m, D/S 0 m. (b) Seepage quantity within RCC dam body, U/S 260 m, D/S 0 m. (c) Seepage quantity within RCC dam body, U/S 267.7 m, D/S 0 m.

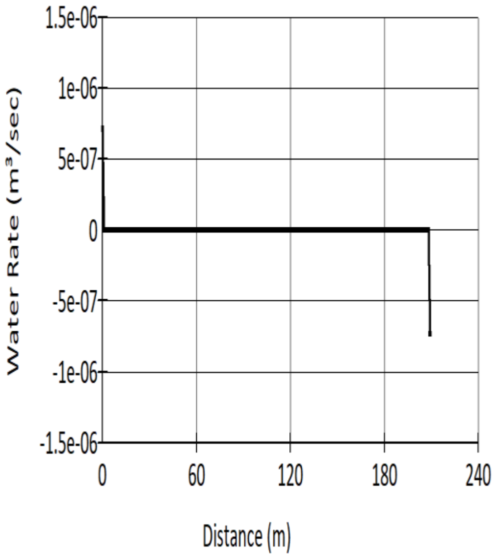
Figure 4.2 (a) gives the seepage profile for the RCC region where seepage profile is taken at the height of 80 m by a line drawn through the RCC region in SEEP/W, where the maximum value ($5.4e^{-13}$ m^3/s) is at the contact point of RCC dam body and water reservoir. In the remaining region, there exists no seepage but of very little value. The low value of permeability of RCC causes it to have negligible seepage within the dam body. Figure 4.2 (b) shows that seepage is more at the upstream face and the downstream face, but shows very little or no value within the dam body. Largest value of seepage ($1.15e^{-12}$ m^3/s) is obtained at the water contact point while lowest value ($-9.10e^{-13}$ m^3/s) is at the point of 153.92 m. This is due to the reason of very low permeability of RCC, because of which negligible seepage occurs within the RCC dam body but it does exist at the uupstream face. Figure 4.2 (c) shows the seepage quantity for RCC section of dam having maximum value of ($1.20e^{-12}m^3/s$) and minimum value of ($-9.60e^{-13}m^3/s$). Maximum value occurs at water contact point (upstream face) of RCC section and very little seepage occurs in the remaining RCC section. Although water level is at free board level, but due to low permeability of RCC, negligible seepage occurs within RCC dam body.

The comparison of Figures (a-c) shows that although there is more seepage observed for the case of maximum water level for working condition and flood condition than the case of minimum water level for working conditions. Also, little difference in seepage values is observed for normal maximum water level condition and flood level condition, means water level variation by a small amount will not change the results.

4.1.3. Seepage quantity at RCC-foundation interface:



(a)



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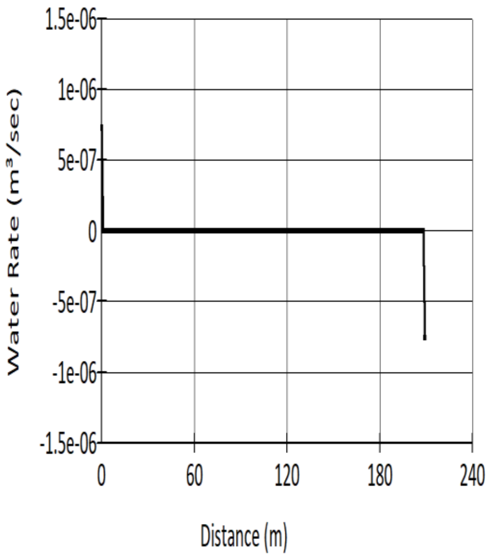
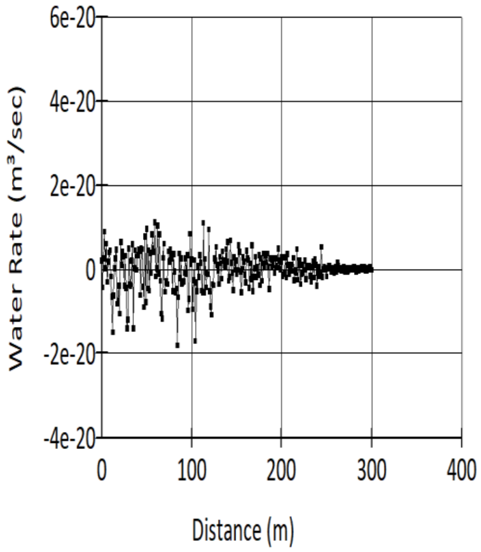


(c)

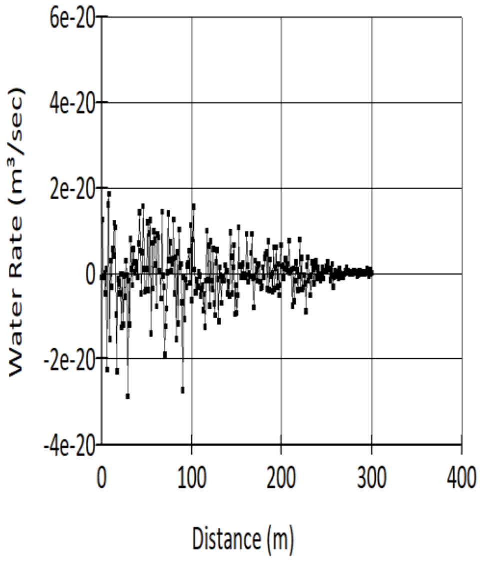
Figure 4.3:(a) Seepage quantity at the RCC dam body-foundation interface, U/S160m, D/S 0 m (b) Seepage quantity at the RCC dam body-foundation interface, U/S 260 m, D/S 0 m (c) Seepage quantity at the RCC dam body-foundation interface, U/S 267.7 m, D/S 0 m.

Figure 4.3 (a) shows that in case of RCC-foundation interface, which is depicted by a line; maximum value of ($4.37e^{-7}$ m^3/s) exists at the toe point and minimum value of ($-4.51e^{-7}$ m^3/s) exists at the heel point. Heterogeneity of the two materials, RCC and bedrock foundation, gives greater value of seepage at the heel. Although both have different permeability but the high permeability of bedrock foundation is dominating here, due to downward seepage of water, causing to have high value of seepage making it critical point of the whole section. In addition, greater value of suction pressure makes the toe section more vulnerable to seepage than the remaining section. Due to suction pressure, cracks might develop at the toe. Figure 4.3 (b) shows the maximum value of seepage ($7.10e^{-7}$ m^3/s) at heel point and minimum value of seepage ($-7.34e^{-7}$ m^3/s) at toe point. Figure (c) shows the maximum seepage quantity of ($7.31e^{-7}$ m^3/s) at heel and minimum seepage quantity of ($-4.1e^{-7}$ m^3/s) toe. The greater value of seepage present at heel is because of the heterogeneity of two materials, RCC and bedrock foundation. In addition, negative pressure is maximum at toe, may cause cracks at toe. This might cause instability, depending upon whether the stress concentration is present at toe or heel. The combination of the negative pore water pressure and stress concentration can make the toe vulnerable if both or any of the two parameters exceed the safe limits.

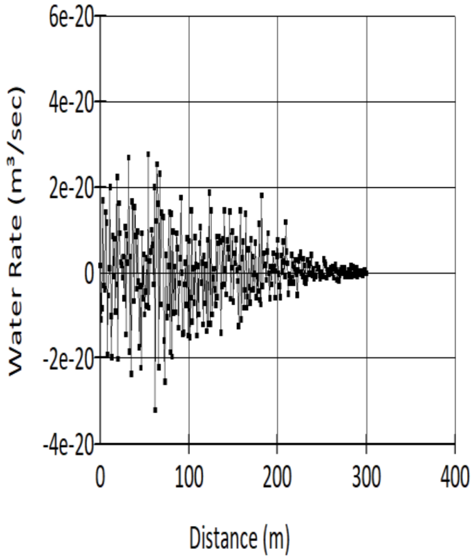
4.1.4. Seepage quantity within bedrock foundation:



(a)



(b)



(c)

Figure 4.4: (a) Seepage quantity in bedrock foundation, U/S 160 m, D/S 0 m (b) Seepage quantity in bedrock foundation, U/S 260 m, D/S 0 m. (c) Seepage quantity in bedrock foundation, U/S 267.7 m, D/S 0 m.

Figure 4.4 (a) shows the seepage quantity for foundation having U/S water level of 160 m and D/S water level of 0 m where maximum seepage quantity ($1.14e^{-20}$ m^3/s) exists at the point of 250 m and minimum seepage quantity ($-1.80e^{-20}$ m^3/s) exists at the point of 212 m. But, in contrast to the other case where total water head is 260 m, greater pore-water pressure exists in the portion ahead of the mid of foundation region. This shows that portion ahead of the mid of foundation regions have more seepage values which can be dangerous for the region lying downstream of foundation. Figure 4.4 (b) shows that seepage is having little value, for the foundation section lying just below the RCC dam body where maximum value of seepage is ($1.87e^{-20}$ m^3/s) at the foundation co-ordinate of 6 m and minimum value of seepage is ($-2.87e^{-20}$ m^3/s) at the foundation co-ordinate of 109 m. Figure 4.4 (c) shows the maximum seepage quantity of ($3.76e^{-20}$ m^3/s) at 51 m and minimum seepage quantity of ($-3.20e^{-20}$ m^3/s) at 34 m, for the condition of U/S water level of 267.7 m and D/S water level of 0 m. There is little difference between the seepage values for the normal maximum water level condition and flood level conditions. Hence, for all the three sections (RCC dam body, RCC-foundation interface, bedrock-foundation), there is little variation in the seepage quantity results and the pore water pressure results. Therefore, it will not be dangerous case to have flood level conditions, for the three sections.

There are sharp peaks and irregularities, which exist for the reason they are found at various nodes along the longitudinal cross-section of the foundation. Mass-balance approach is applied here; so, asto follow the equation of continuity, seepage is varying at each node in both positive and negative directions. This happens subsequently at all the nodes of the elements, as they are analyzed in SEEP/W. Positive pore water pressure and suction pressure both are present but at different nodes of the same element. This depends upon the meshing size and boundary conditions of the nodes. That’s the way, pore water pressure varies from upstream to downstream of foundation, changing from higher values at upper end to negligible values at the downstream end. As the seepage occurs through the foundation, the impermeable nature of foundation cause the seepage quantity to decrease towards the downstream end.

4.2. Seepage behaviour of dam body (full reservoir level, steady state condition):

4.2.1. Pore water pressure profile:

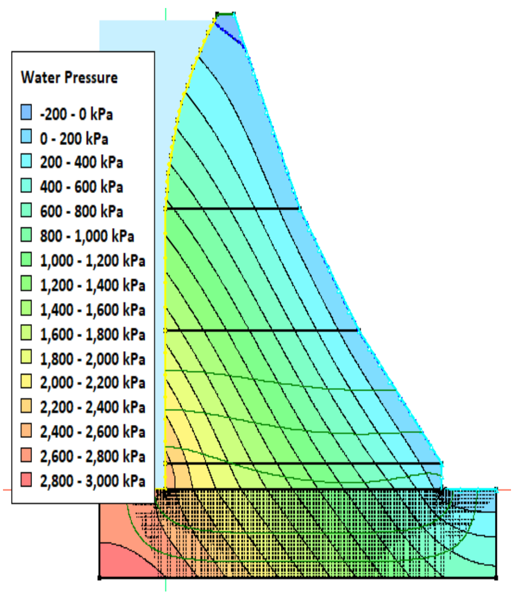
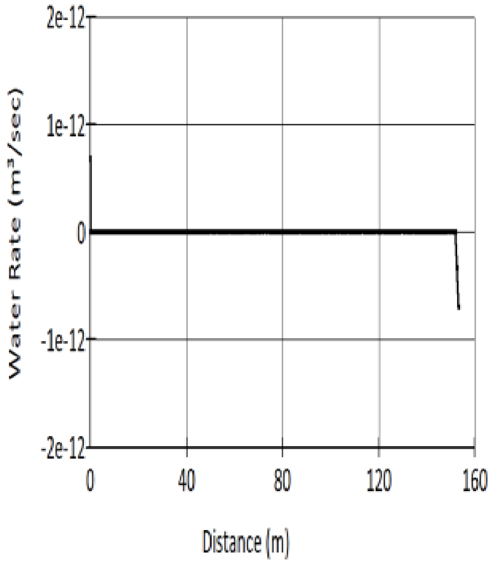


Figure 4.5: pore water pressure profile,

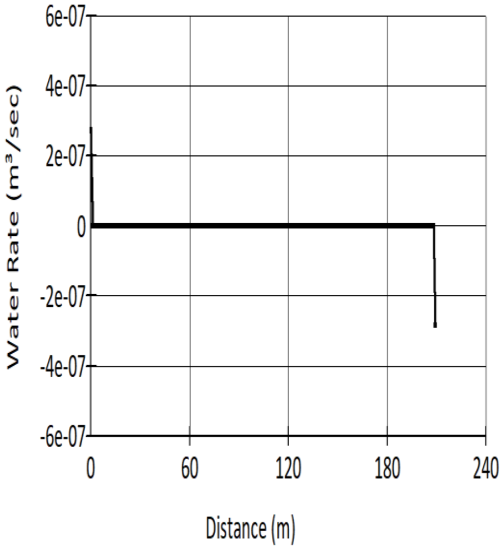
U/S 260 m, D/S 160 m

Figure 4.5 shows the pore water pressure which varies from -200 kPa at top of the dam section (free board), within RCC and 3000 kPa at the right most edge of the dam foundation.

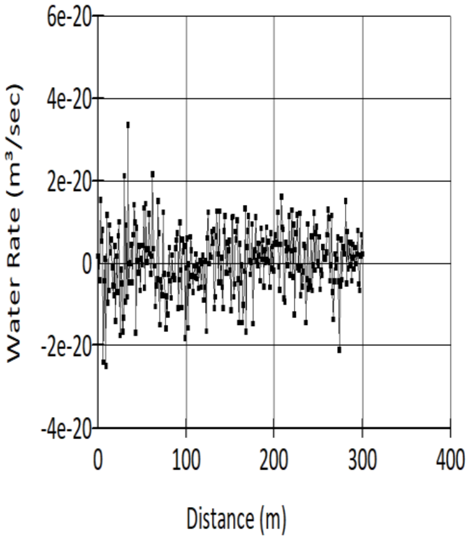
4.2.2. Seepage quantity in RCC dam body, RCC-foundation interface, bedrock foundation:



(a)



(b)



(c)

Figure 4.6: (a) Seepage quantity within RCC dam body, (b) seepage quantity at the RCC dam body-foundation interface, (c) seepage quantity in Gabbro rock foundation, U/S 260 m, D/S 160 m

Figure 4.6 (a) gives the observation that seepage at U/S face is of considerable value than the remaining section which confirms the vulnerability of the U/S face for steady state conditions. Figure 4.6 (b) shows the greater value of seepage at the heel as compared to the toe and the maximum value of seepage is 2.74e^{-7} m^3/sec, obtained at the U/S face. Again, vulnerability of the U/S face for the full reservoir level condition is observed. Figure 4.6 (c) shows that for foundation, maximum value of seepage is 2.95e^{-20} m^3/seconds and seepage is varying randomly with no specific pattern.

4.3. Seepage behaviour of dam body, rapid draw down condition:

4.3.1. Pore water pressure profile:

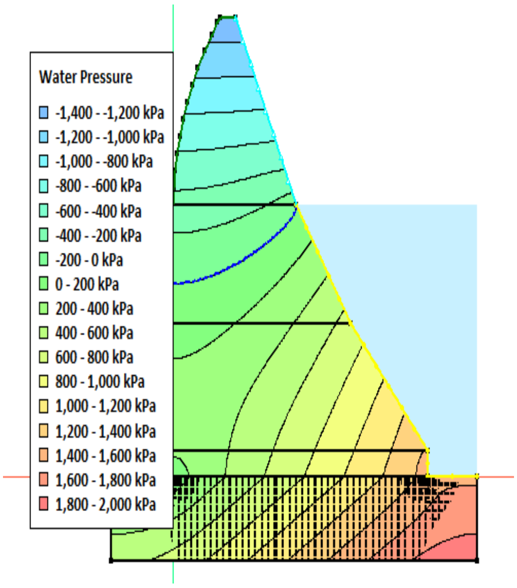
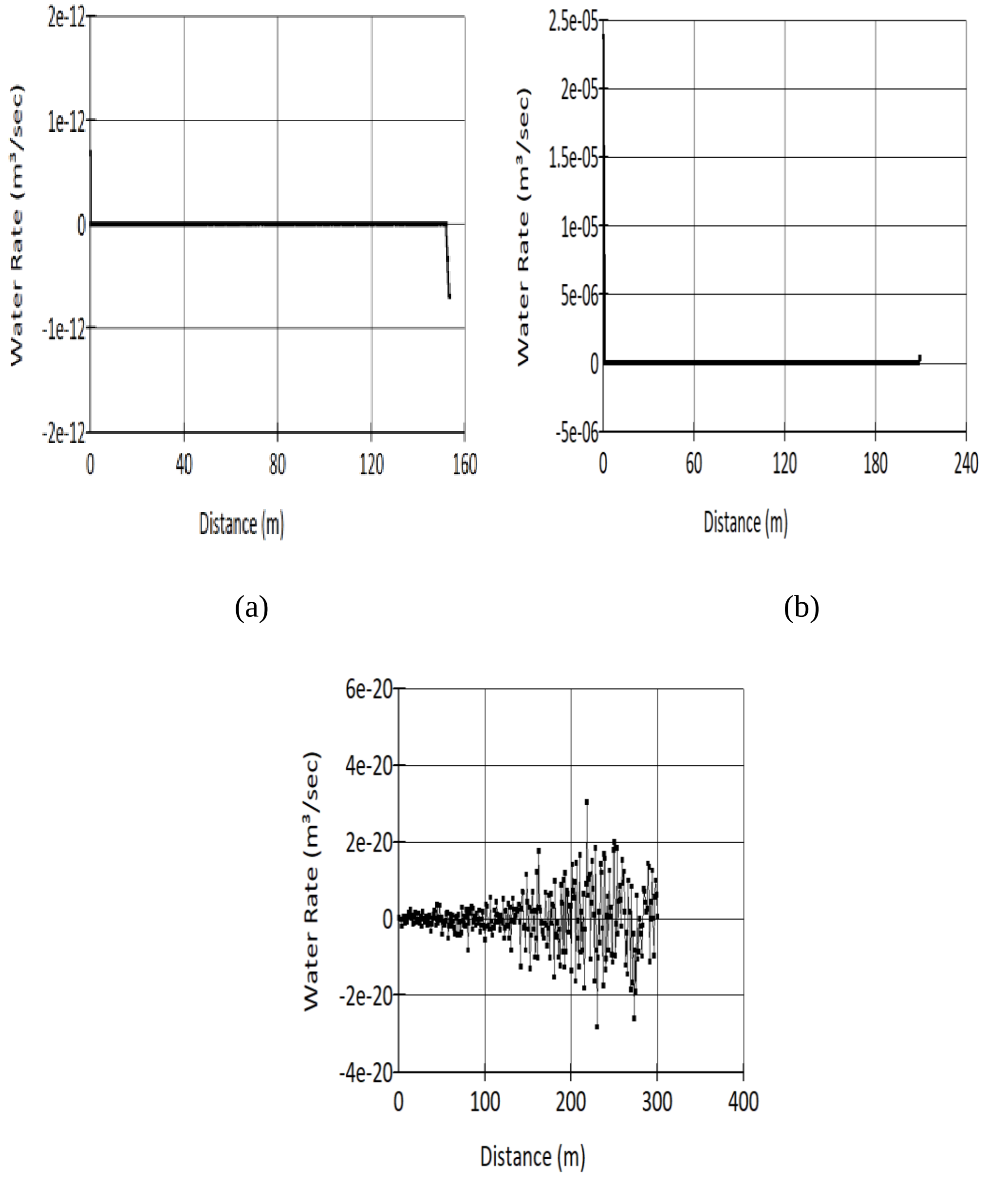


Figure 4.7: Pore water pressure profile,U/S 0 m, D/S 160 m

Figure 4.7shows the pore water pressure which varies from -1400 kPa at top of the dam section (free board) within RCC and 2000 kPa at the right corner of the dam foundation which shows that pore water pressure is very different fromsteady state conditions because of the rapid draw-down condition. Phreatic line is lying at low level and negative pressure is more at the top but having high value within the RCC dam body which might cause suction pressure and crack initiation. In addition, maximum pore water pressure is at the D/S end of foundation, which might be very dangerous for the stability of dam.

4.3.2. Seepage quantity within RCC dam body, RCC-foundation interface, bedrock foundation:



(a) (b)

(c)

Figure 4.8: (a) Seepage quantity within RCC dam body, (b) Seepage quantity at the RCC dam body-foundation interface, (c) Seepage quantity in Gabbro rock foundation, U/S 260 m, D/S 0 m.

Figure 4.8 (a) shows that seepage at the U/S face is negligible as compared to the D/S face which is in contrast to the greater value of seepage at U/S face and negligible value at D/S face in steady state conditions. This shows the vulnerability of the D/S face in transient conditions. Figure 4.8 (b) shows the greater value of seepage at the toe as compared to the heel which shows that in transient state seepage conditions, seepage patterns are exactly opposite to the steady state seepage. The anticipation of negative pressure at the U/S face might cause crack generation and fracture development. Figure 4.8 (c) shows that in case of foundation, seepage is more at D/S end of foundation and negligible at U/S end of foundation which is also in contrast with the steady state condition. This shows that in case of transient condition, seepage patterns are different from steady state condition might be difficult to mitigate. This way, length of seepage path will be greater than the normal working condition and also greater width will be impacted because of different conditions.

4.4. Variation of pore water pressure and seepage quantity for changes in water level:

Table 4.2Variation of pore water pressure and seepage with water level

S. no /-	Water Level (m)		Seepage range (m^3/sec)			Pore water pressure (kPa)	Condition
	U/S (m)	D/S (m)	RCC seepage(m^3/sec)	RCC-foundation interface. sseepage(m^3/sec)	Foundation seepage(m^3/sec)	pwp (kPa)	
1	160	0	$+5.4e^{-13}$, -1.4^{-13}	$4.37e^{-7}$, $-4.51e^{-7}$	$1.14e^{-20}$, $-1.80e^{-20}$	-1400, 2000	Post construction stage (min. water level)
2	260	0	$1.15e^{-12}$, $-9.10e^{-13}$	$7.1e^{-7}$, $-7.34e^{-7}$	$1.87e^{-20}$, $-2.87e^{-20}$	-200, 3000	Post construction stage (max. water level)
3	267.7	0	$1.20e^{-12}$, $-9.6e^{-13}$	$7.31e^{-7}$, $-4.1e^{-7}$	$3.76e^{-20}$, $-3.20e^{-20}$	-200, 3000	Post construction stage (flood level)
4	260	160	$6.84e^{-13}$, $-6.9e^{-13}$	$2.74e^{-7}$, $-2.82e^{-7}$	$2.95e^{-20}$, $-2.85e^{-20}$	-200, 3000	Steady state seepage
5	0	160	$9.03e^{-13}$, $-1.18e^{-13}$	$4.51e^{-7}$,$-4.38e^{-7}$	$1.95e^{-20}$, $-2.29e^{-20}$	-1400, 2000	Rapid draw down (transient state)

- The reason for the selection of 3 limiting levels for post construction stage is that post construction stage 1 deals with normal minimum operating level of dam where U/S has water level of 160 m and D/S has water level of 0 m. While, post construction stage 2 has normal maximum operating level where U/S water level is 260 m and D/S has 0 m. Third level deals with flood condition, where U/S water level is 267.7 m and D/S water level is 0 m. It is necessary to analyze the dam geometry for the worst case scenario expected, which is flood. That's why there are 3 post construction limiting levels for the dam body.

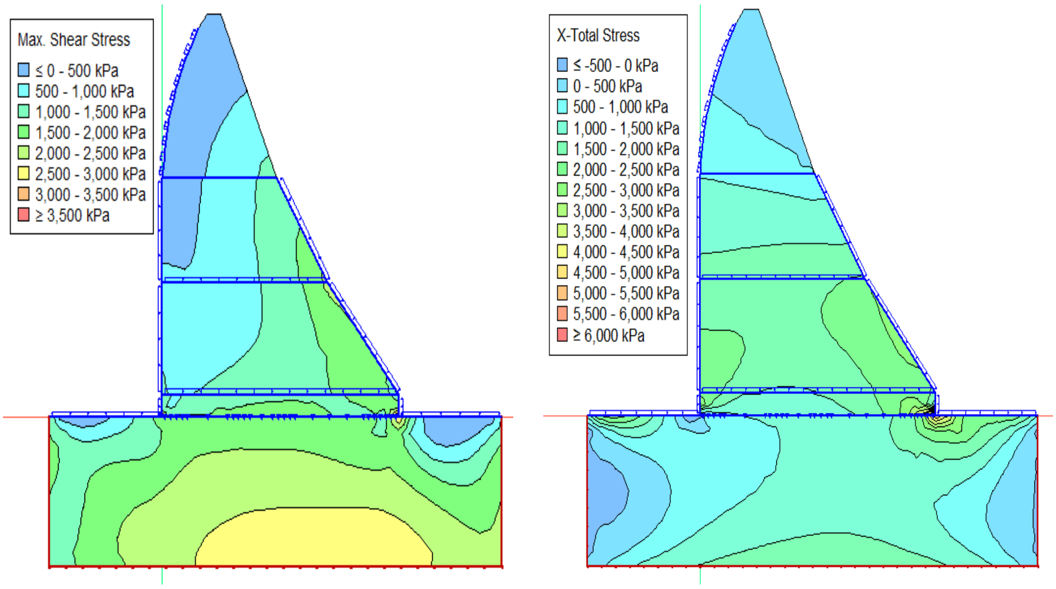
- If the values of results obtained from steady state seepage condition and transient state seepage condition are obtained, these values differ greatly in context of pore water pressure. As for the remaining seepage values are concerned, which are found at RCC-foundation interface, within RCC dam body and within bedrock foundation, there is not much difference as the order of variation is not changed but only the initial constants are changed. This shows that seepage values depend upon the permeability of the material (RCC or bedrock foundation) and changes if the nature of material is changed. Increase in water level on any sides of the dam will not cause much difference for seepage. So, permeability is important parameter for defining the trend of seepage potential for the dam.
- Also, by comparing the results of different conditions; in post-construction stage, the case of flood level for the dam body has highest seepage values for RCC dam body, RCC-foundation interface and bedrock foundation. This proves that for the post construction stage, worst-case scenario will be of flood level on U/S. Not only for the condition of post-construction stage but for steady state seepage and rapid draw down conditions, the worst case scenario among all conditions will be of post-construction stage having flood level. However, these values are within allowable limits. As for the limit of seepage velocity values which might cause erosion and harmful scour for loose earth and rocks is concerned, the limits are (0,1-6,0) m/s. From the seepage analysis done, maximum value found for the bedrock foundation is for the case having maximum water level correspondent to flood level, and here the seepage velocity in X direction is $4.47e^{-8}$ m/sec and for Y direction, it is $4.69e^{-8}$ m/sec. Hence, seepage velocity values for foundation are within prescribed limits, which is showing that no safety measures are needed for prevention of seepage.

4.5. Stress analysis results:

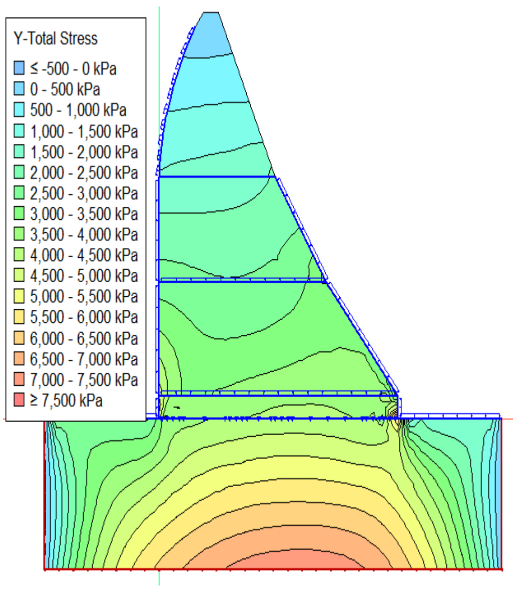
4.6. Stress analysis for dam cross-section with no grout curtains:

This section deals with the results obtained from the stress analysis. Different types of stresses such as shear stress, X-directional stress, Y-directional stress, Z-directional stress, maximum total stress and minimum total stress are part of this section. Further, the impact of addition of different grout curtains upon the stresses and displacements within the dam body and the foundation is also discussed. The results obtained from the stress analysis are discussed here for 2 different conditions. First is the dam geometry without any inclusion of grout curtains and in second condition, a number of grout curtains (1:4) are also part of the structure.

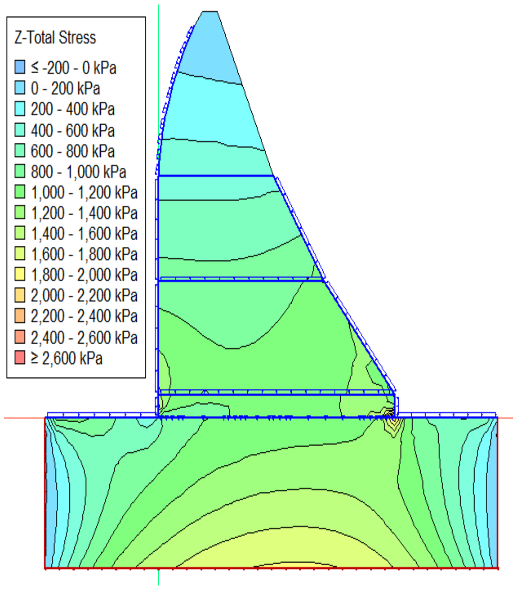
4.6.1. Shear stress, stress in X, Y, Z directions, maximal total stress, minimal total stress:



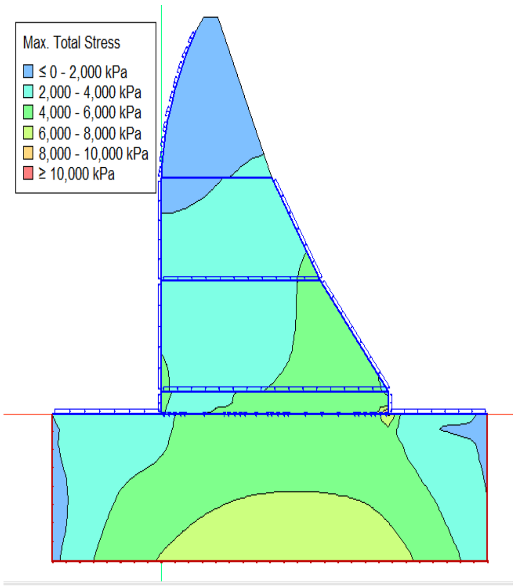
(a) (b)



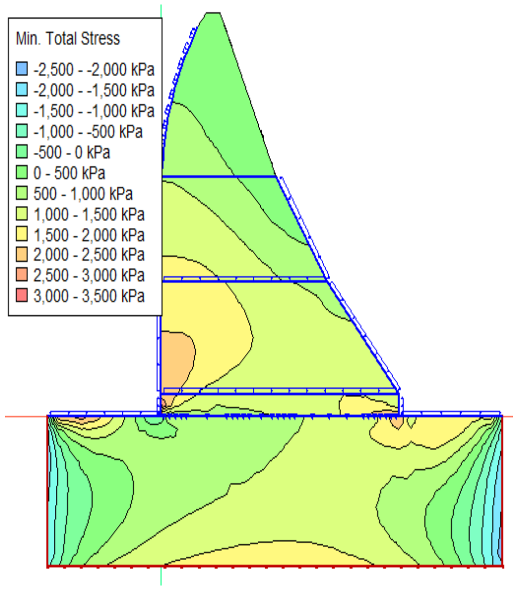
(c)



(d)



(e)

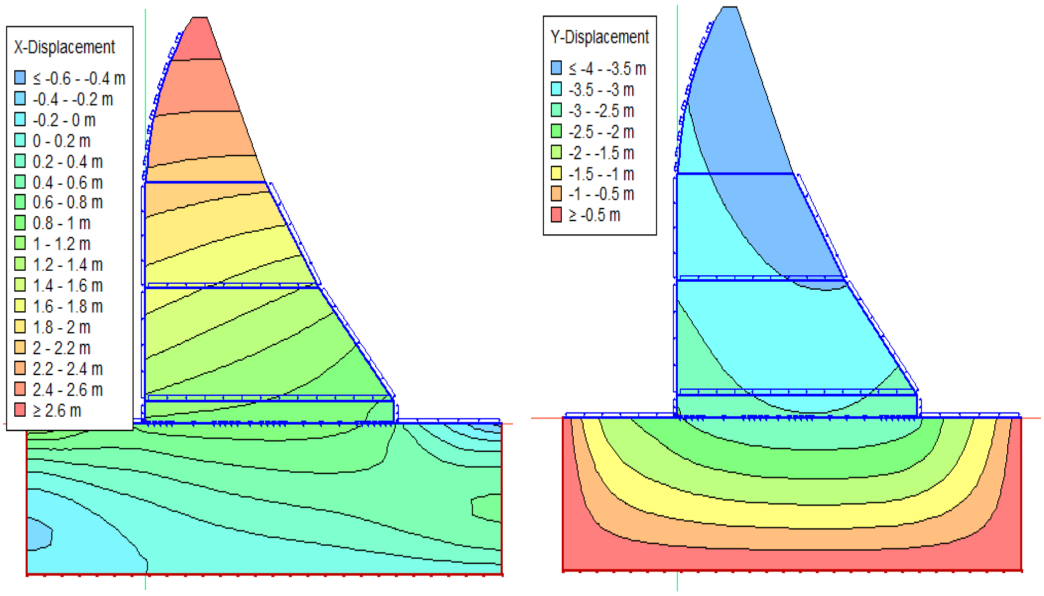


(f)

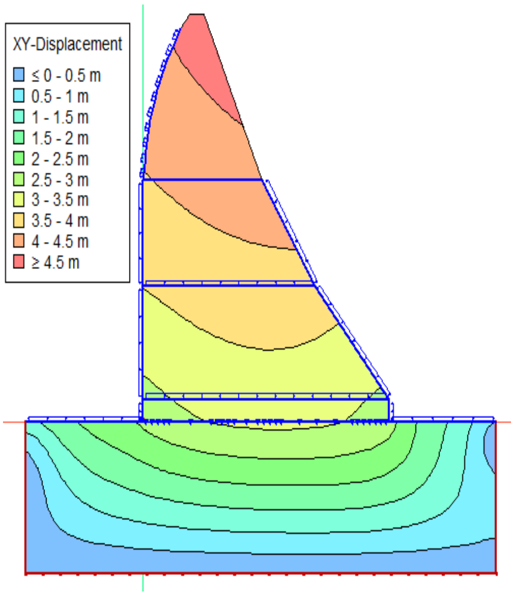
Figure 4.9: (a) Shear stress in the dam section, (b) Stress in X direction, (c) Stress in Y direction, (d) Stress in Z direction, (e) Maximal total stress, (f) Minimal total stress.

Figure 4.9 (a) shows the shear stresses in the structure, which varies from 0 MPa to more than 3.5 MPa in the foundation. There is not much difference between the values obtained from the analysis involving grout curtains and their exclusion, which shows absence of grout curtains, has no significant effect on shear stresses. Figure 4.9 (b) shows the total stresses in the X direction which varies from 0.5 MPa (tension) to more than 6 MPa (compression). The stresses in the X direction change considerably for the case excluding grout curtains. Also, no uniformity in the values across the cross-section is observed. Figure 4.9 (c) shows the stresses in the Y direction, which vary from 0.5 MPa (tension) to more than 7.5 MPa (compression). There is significant difference observed between the values in the cases involving grout curtains. Figure 4.9 (d) shows stresses in the Z direction, which vary from 0.2 MPa (tension) to more than 2.6 MPa (compression). There is not much variation regarding stresses in Z direction for the cases involving grout curtains and their exclusion. Figure 4.9 (e) shows the maximum total stress which vary from 0 MPa (compression) to more than 10 MPa (compression). Similar results are obtained from previous case involving grout curtains. Figure 4.9 (f) shows minimal total stresses which vary from -2.5 MPa (tension) to 3.5 MPa (compression). Almost similar results are obtained from the case having grout curtains, means no significant difference for minimal stresses.

4.6.2. Displacements in X, Y, XY direction:



(a) (b)



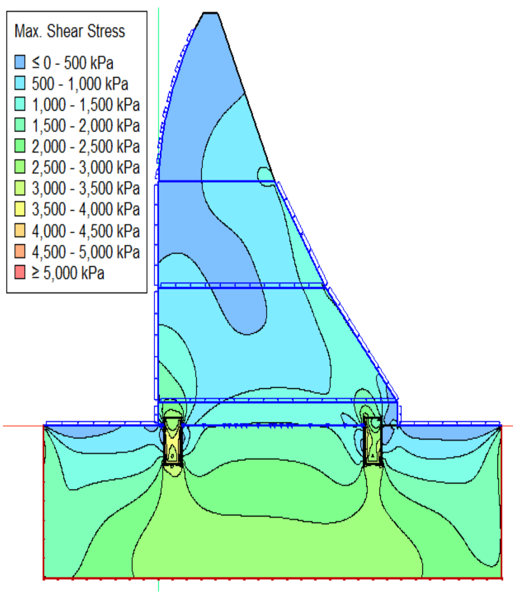
(c)

Figure 4.10: (a) Displacement in X direction, (b) Displacement in Y direction, (c) Displacement in XY direction

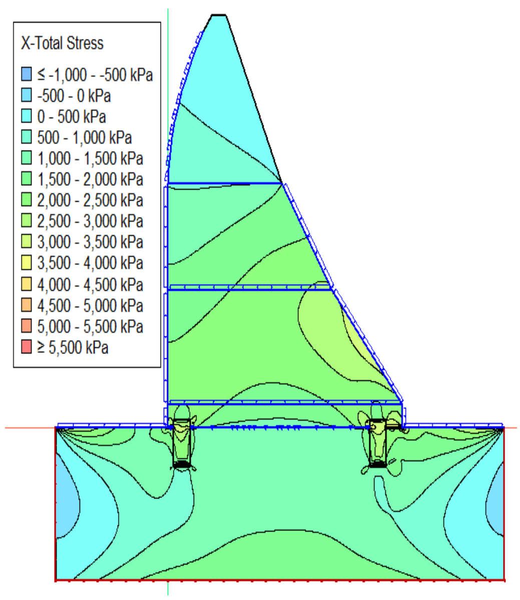
Figure 4.10 (a) shows the displacements of the structure as water action is made on it. Top of the structure is tilted 40-60 cm in the negative X direction while the remaining part of RCC structure shows abrupt changes in the displacement values. The greatest value found for the displacements in x direction is 2.6 m which is very large value. This shows how the exclusion of grout curtains will affect the displacement values. Figure 4.10 (b) shows the displacements of whole dam body in the Y direction, which vary from -0.5 m to -4 m. The dam bedrock foundation is experiencing negative displacements. Again, there are large displacements when there are no grout curtains. Figure 4.10 (c) depicts positive displacements in the XY direction which ranges from 0 m to more than 4.5 m. The dam bedrock foundation is experiencing larger displacements as contrast to the cases involving grout curtains.

4.7. Stress analysis for dam cross-section with 2 grout curtains:

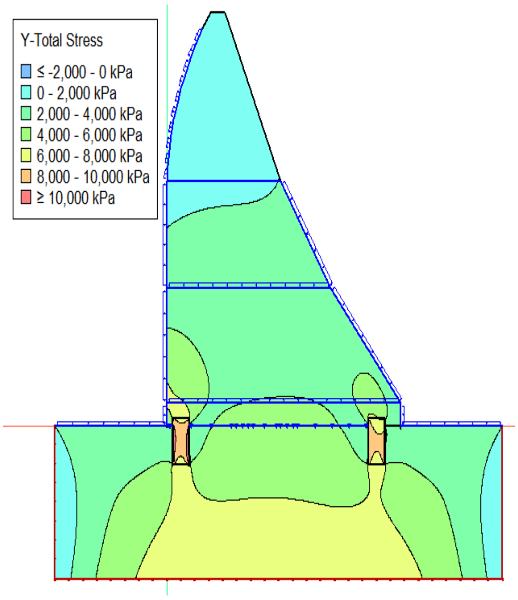
4.7.1. Shear stress, stress in X, Y, Z directions, maximal total stress, minimal total stress:



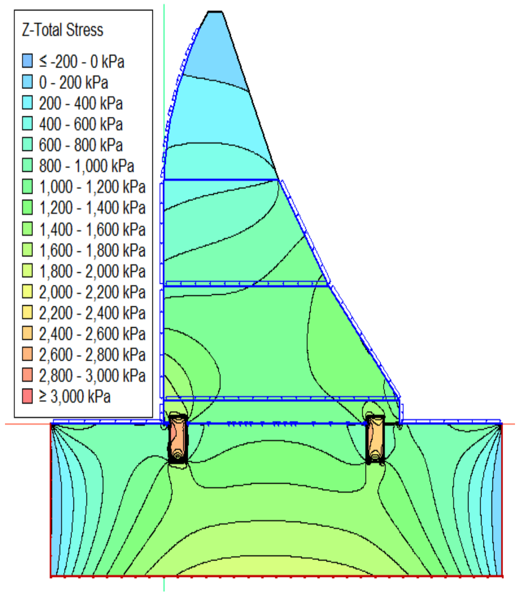
(a)



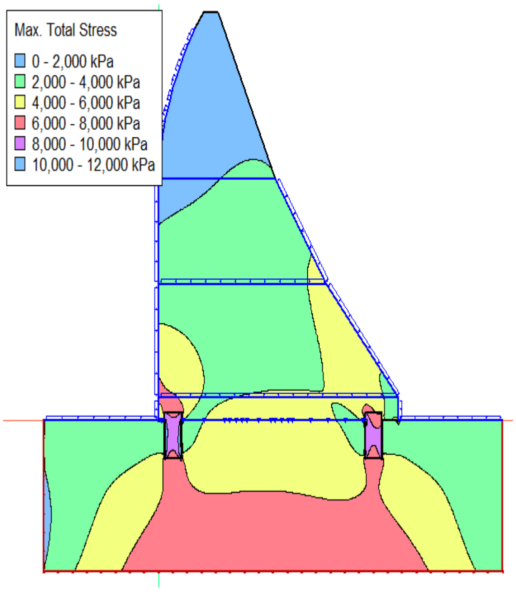
(b)



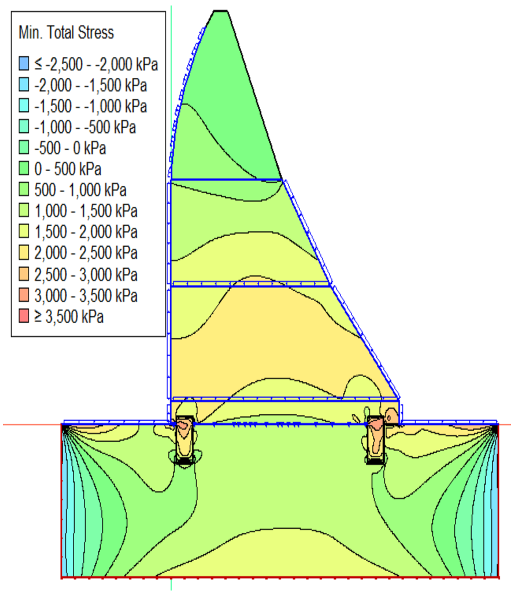
(c)



(d)



(e)



(f)

Figure 4.11: (a) Shear stress in the dam section, (b) Stress in X direction, (c) Stress in Y direction, (d) Stress in Z direction, (e) Maximal total stress, (f) Minimal total stress.

Figure 4.11 (a) shows the shear stress variation within the dam body where the minimum value of shear stress is 0 MPa and maximum value is 5 MPa. There is much variation of shear stress in the region around the grout curtains means that grout curtains can significantly impact the shear stress. Figure 4.11 (b) shows the stresses in the X direction where minimum value of X-directional stress is -1 MPa (tension) while maximum value is 5.5 MPa (compression). Again, the impact of grout curtains can be seen, in the form of stress concentration around the grout curtains. Figure 4.11 (c) depicts the stresses in the Y direction, where the minimum value is -2 MPa (tension) and the maximum value is 10 MPa (compression). Figure 4.11 (d) shows the stresses in the Z direction, where minimum value is -0.2 MPa (tension) and maximum value is 3 MPa (compression). Figure 4.11 (e) shows that the maximum total stress value is lying between 0 MPa and 12 MPa (compression). Figure 4.11 (f) shows the minimum total stress value, which lies between -2.5 MPa (tension) and 3.5 MPa (compression).

4.7.2. Displacements in X, Y, XY direction:

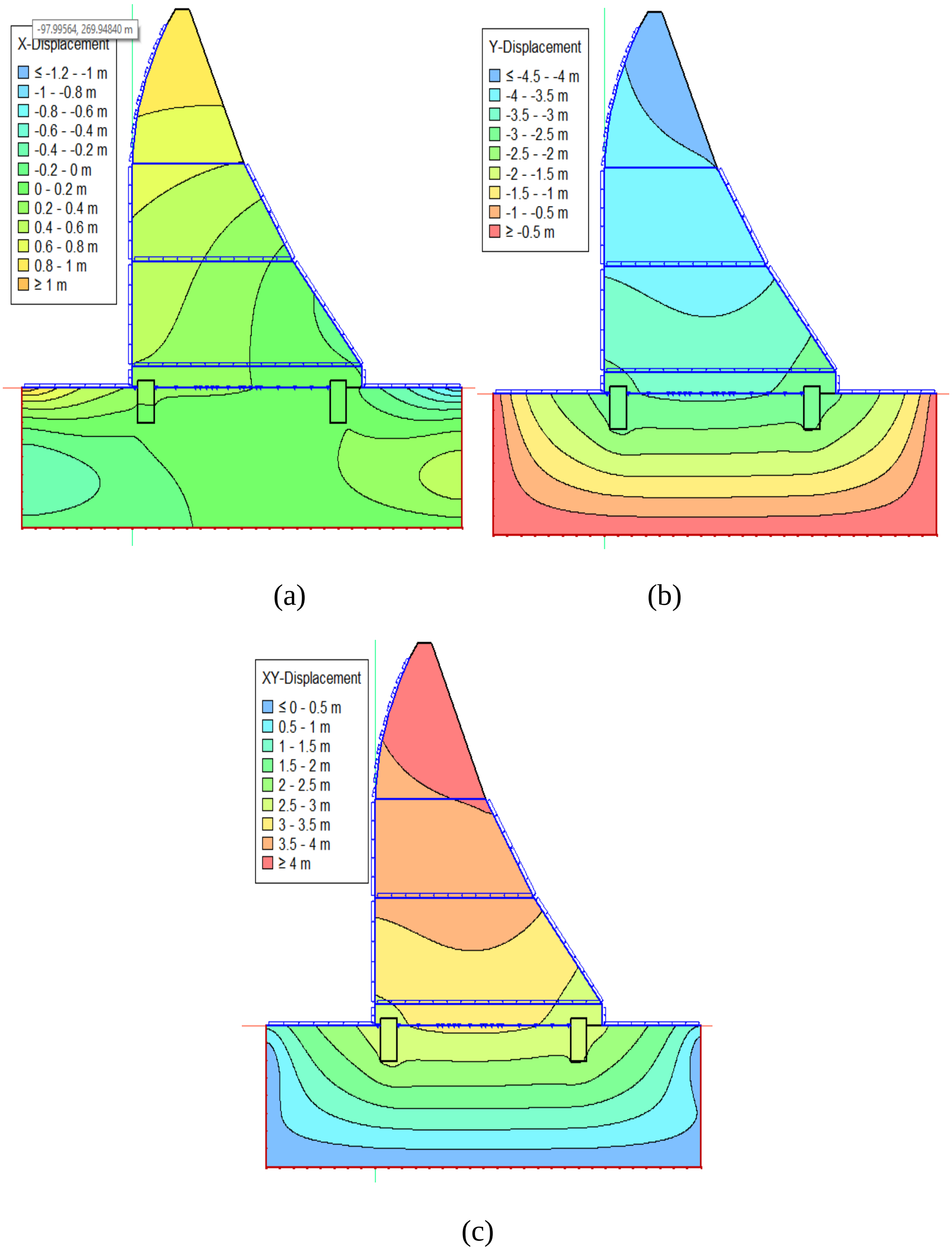


Figure 4.12: (a) Displacement in X direction, (b) Displacement in Y direction, (c) Displacement in XY direction.

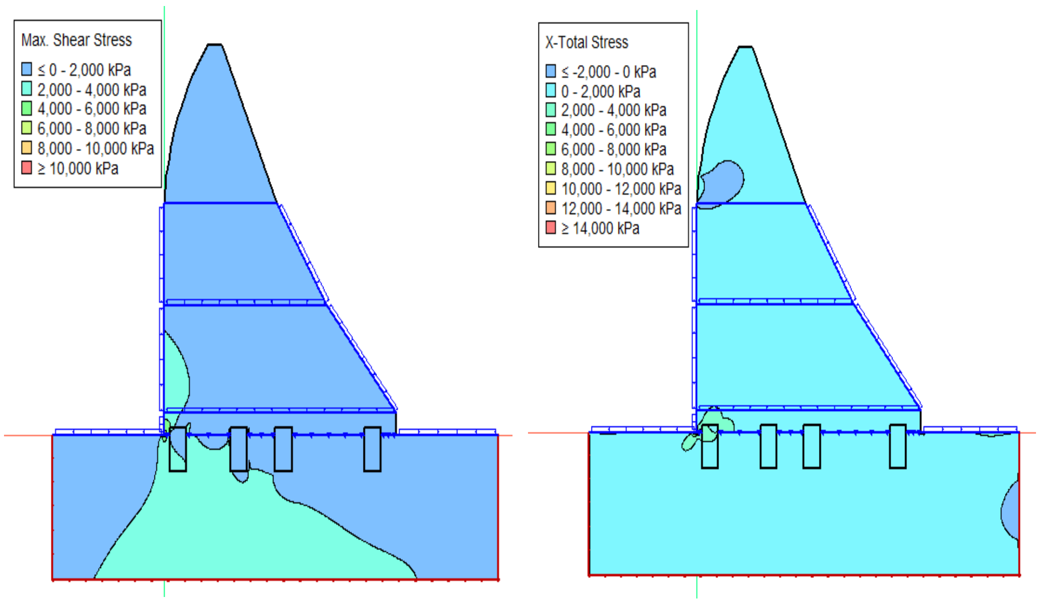
Figure 4.12 (a) is showing the displacements in X direction, which lies between -120 cm (leftward movement) and 100 cm (rightward movement). Figure 4.12 (b) depicts that the minimum displacement observed in Y direction is -50 cm and maximum value obtained is -450 cm (settlement). Figure 4.12 (c) shows the minimum displacement in XY direction having values between 0 cm and 400 cm.

4.8. Stress analysis for dam cross-section with 4 grout curtains:

4.8.1. Minimum water level conditions:

Here, normal minimum water level for working conditions is 160 m on U/S and 160 m on D/S.

4.8.2. Shear stress, stress in X, Y, Z directions, maximal total stress, minimal total stress:



(a) (b)

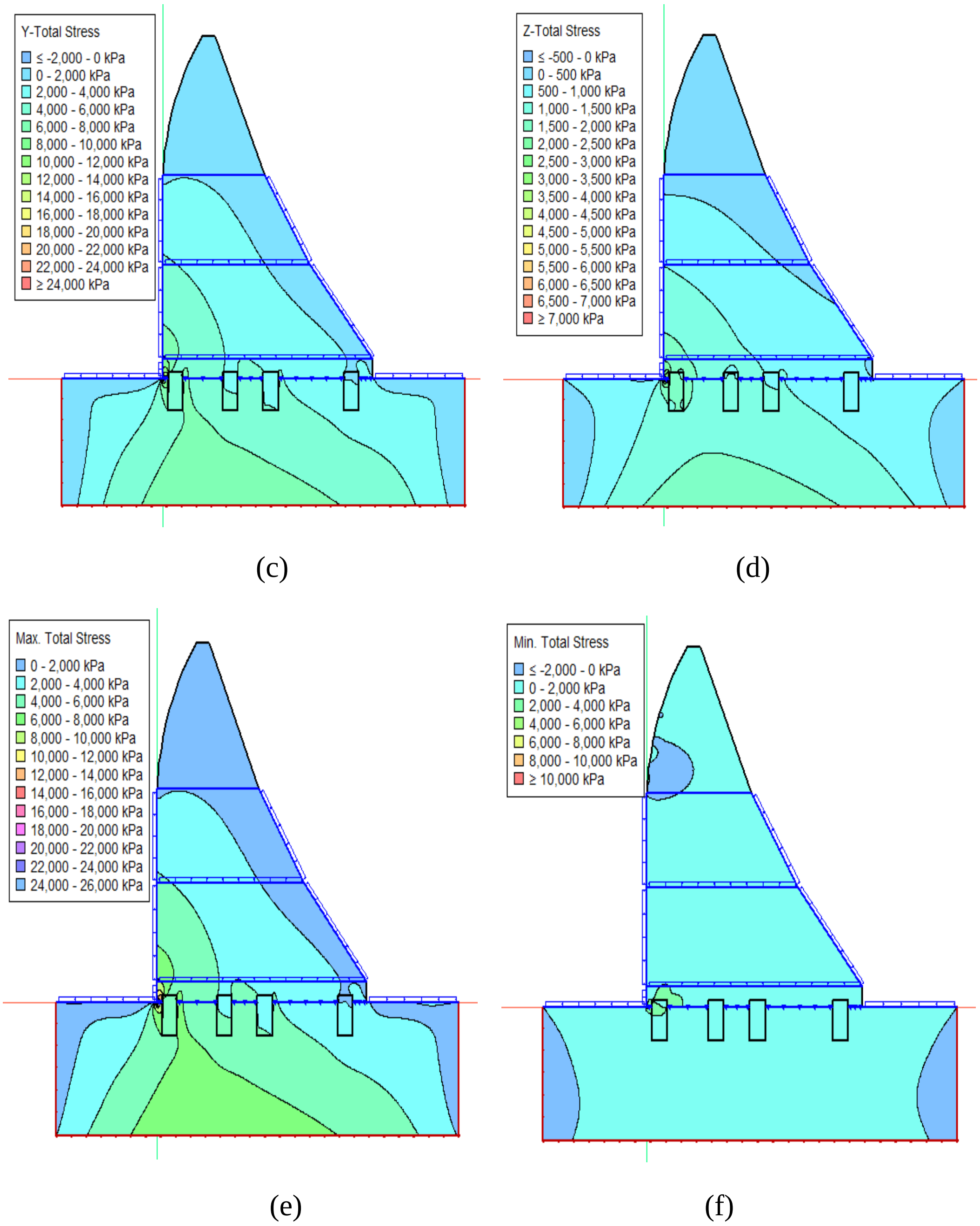
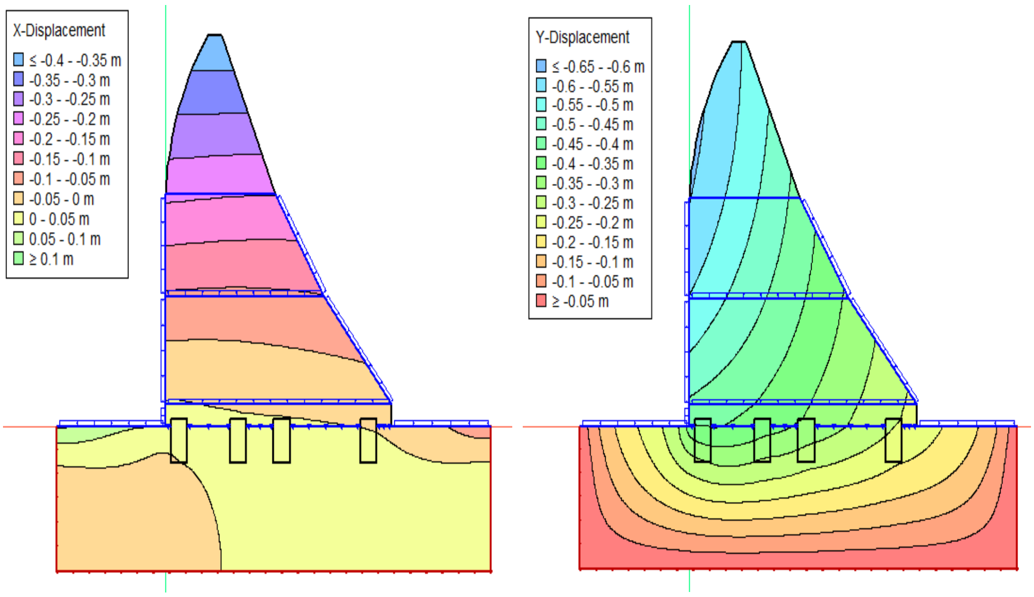


Figure 4.13: (a) Shear stress in the dam section, (b) Stress in X direction, (c) Stress in Y direction, (d) Stress in Z direction, (e) Maximum total stress, (f) Minimal total stress

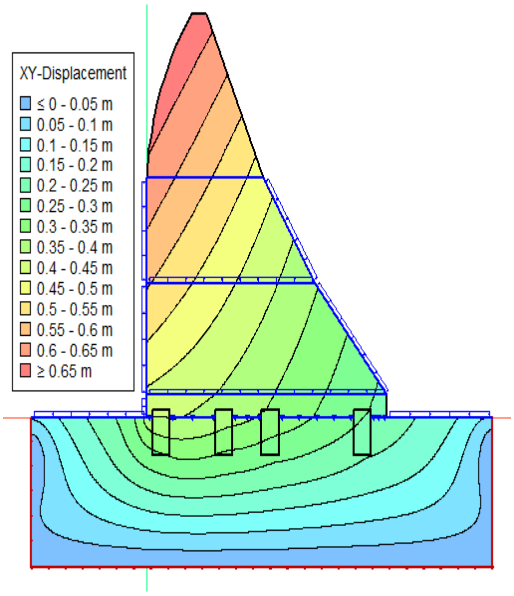
Figure 4.13 (a) shows the shear stresses in the structure, which varies from 0 MPa to more than 10 MPa in the foundation. Maximum value of 10 MPa exists around the ground curtains and minimum value of 0 MPa exists in the top portion in the RCC region of the dam body.Figure 4.13 (b) shows the total stresses in the X direction which varies from 2 MPa (tension) to more than 14 MPa (compression). Maximum value of

14 MPa exists at the heel. Figure 4.13 (c) depicts the stresses in the Y direction which vary from 2 MPa (tension) to more than 24 MPa (compression) where maximum value of 24 MPa exists at the heel portion of the dam. Figure 4.13 (d) shows stresses in the Z direction, which vary from 0.5 MPa (tension) to more than 7 MPa (compression), the maximum value exists at the heel portion of the dam. Figure (e) gives the maximum total stresses that vary from 0 MPa (compression) to more than 26 MPa (compression). More stress variation occurred in the region around the ground curtains. Figure 4.13 (f) gives the values of minimal total stresses which varyfrom 2 MPa (tension) to 10 MPa (compression). Most of the dam cross-section has lower stress values.

4.8.3. Displacements in X, Y, XY direction:



(a) (b)



(c)

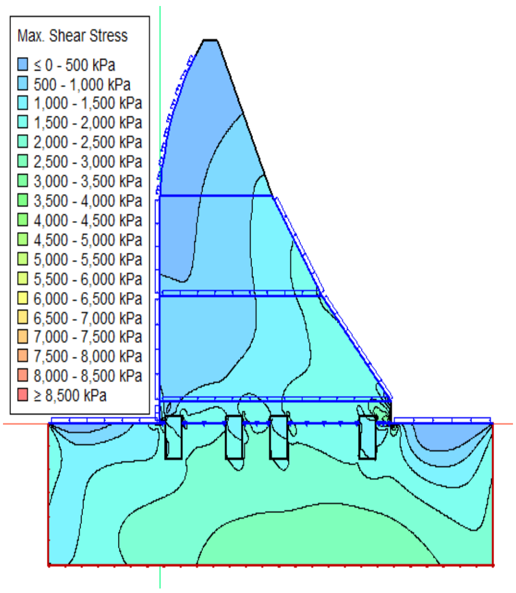
Figure 4.14: (a) Displacement in X direction, (b) Displacement in Y direction, (c) Displacement in XY direction.

Figure 4.14 (a) shows the displacement of the structure as water action is made on it. Top of the structure is tilted 4.5-5 cm in the negative X direction while the remaining part of RCC structure shows abrupt changes in the displacement values. The RCC-foundation interface shows very little settlement, less than 100 of millimeters, which shows the critical region is safe against displacement. Figure 4.14 (b) shows the displacement of whole dam body in the Y direction that varies from-65 cm to -5 cm. The dam bed rock foundation is experiencing negative displacements .Figure 4.14 (c) shows the displacements in the XY direction that varies from 0 cm to more than 65 cm. The dam bedrock foundation is experiencing very little displacements.

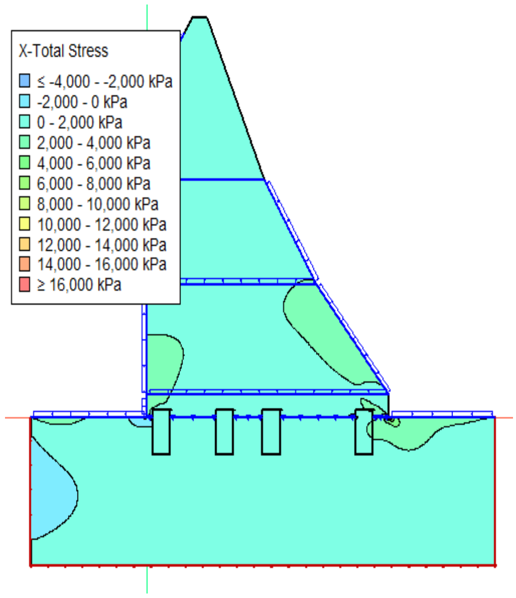
4.8.4. Maximum water level conditions:

Here, water at U/S level is having the height of 260 m and D/S is 160 m, with other loads as uplift pressure and self weight also applied on the structure.

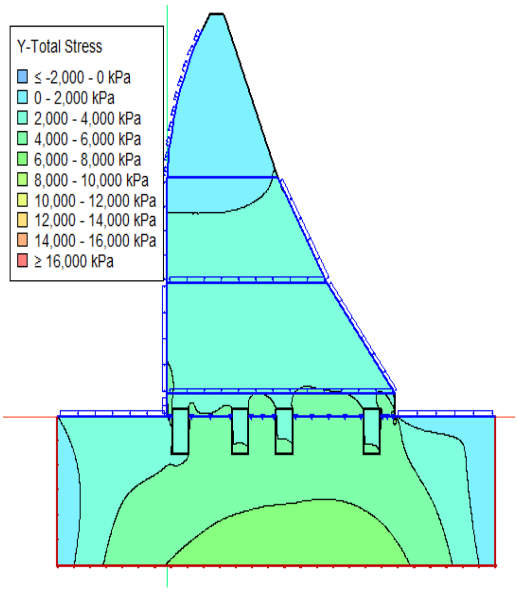
4.8.5. Shear stress, stress in X, Y, Z directions, maximal total stress, minimal total stress:



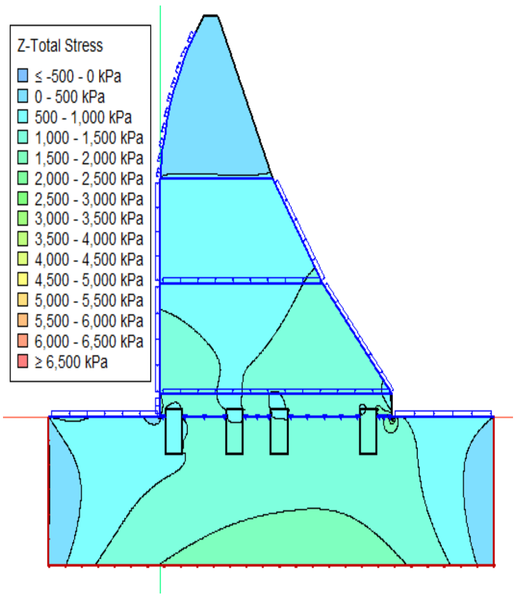
(a)



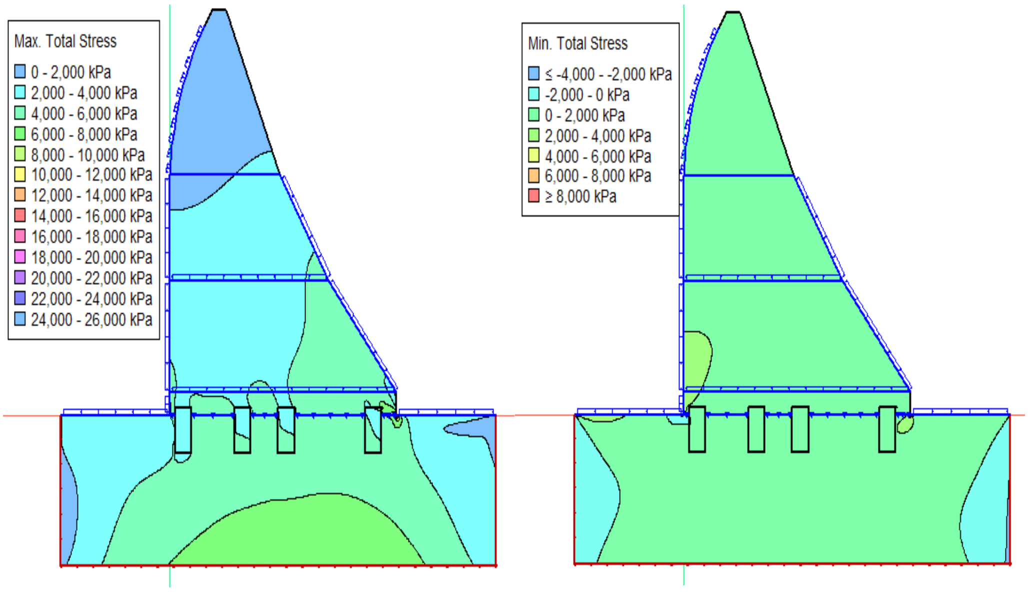
(b)



(c)



(d)

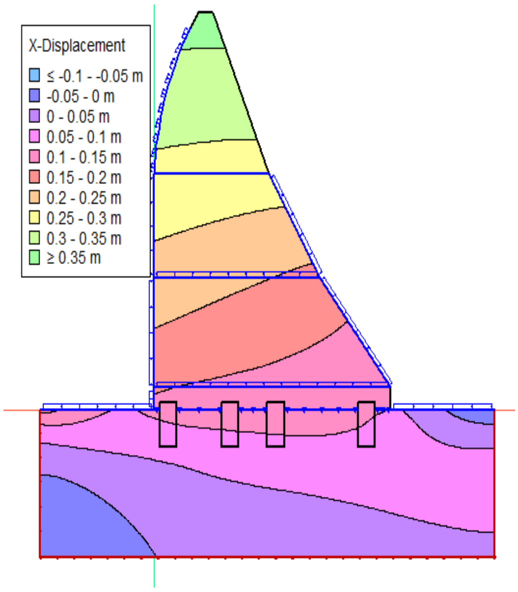


(e) (f)

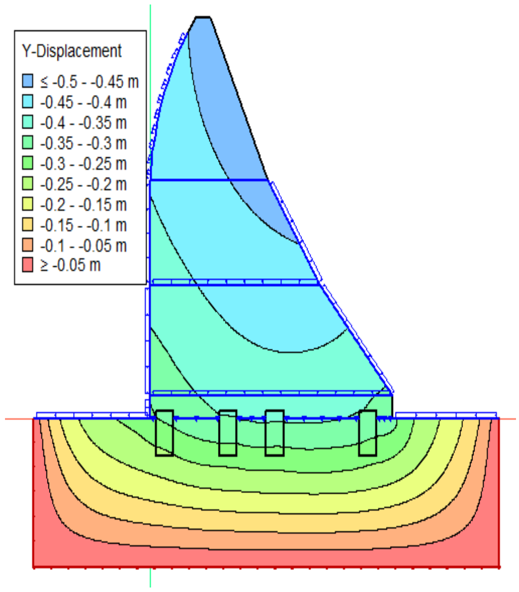
Figure 4.15: (a) Shear stress in the dam section, (b) Stress in X direction, (c) Stress in Y direction, (d) Stress in Z direction, (e) Maximal total stress, (f) Minimal total stress.

Figure 4.15 (a) shows the shear stresses in the structure, which varies from 0 MPa to more than 8.5 MPa in the foundation where maximum value of 8.5 MPa exists around the ground curtains. Figure 4.15 (b) shows the total stresses in the X direction which varies from 4 MPa (tension) to more than 16 MPa (compression). Figure 4.15 (c) shows the stresses in the Y direction that vary from 2 MPa (tension) to more than 16 MPa (compression) where maximum value of 16MPa exists at the heel of the dam. Figure 4.15 (d) shows stresses in the Z direction which vary from 0.5 MPa (tension) to more than 6.5MPa (compression), the maximum value exists at the heel of the dam. Figure 4.15 (e) shows maximum total stress which vary from 0 MPa to more than 26 MPa (compression). More stress variation occurred in the region around the ground curtains. Figure 4.15 (f) shows the minimal total stresses which varies from 4 MPa (tension) to 8 MPa (compression). Most of the dam cross-section has lower stress range.

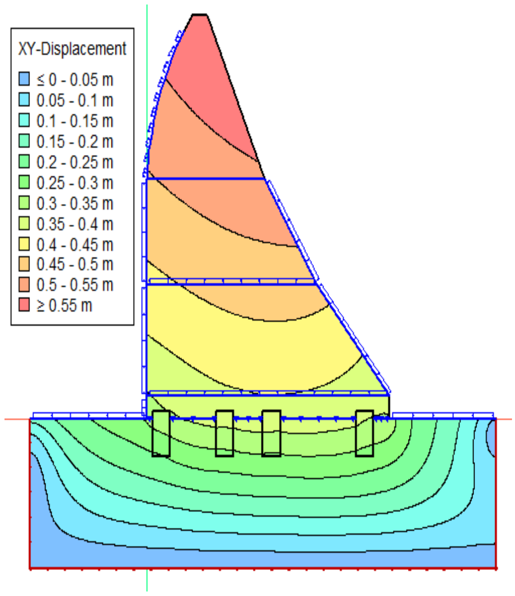
4.8.6. Displacements in X, Y, XY direction:



(a)



(b)



(c)

Figure 4.16: (a) Displacements in X direction, (b) Displacements in Y direction, (c) Displacements in XY direction.

Figure 4.16 (a) shows the displacement of the structure as water action is made on it. Top of the structure is tilted 35 cm in the positive X direction while the remaining part of RCC structure shows abrupt changes in the displacements values. The RCC-foundation interface shows little displacement about 10 cm. Figure 4.16 (b) shows the displacement of whole dam body in the Y direction which varies from -5 cm to-50 cm. The dam bedrock foundation is experiencing negative displacements and there is abrupt displacement variation in the base of dam body. Figure 4.16 (c) shows that the displacements in the XY direction are positive and have values between 0 cm and 55 cm. The dam bedrock foundation is experiencing wide variation in displacements.

4.8.7. Comparison and discussion for different conditions of grout curtains:

Table 4.3 shows the comparison of different parameters which showed that different parameters vary greatly and differently with the addition of grout curtains. Although the displacements are reduced to a much lower value, and the stresses are increasing but the purpose of addition of grout curtains at different lengths along the RCC-foundation interface is to reduce the displacements, which is obviously achieved. The stresses are increasing (total maximal stresses have value between 0-26 MPa) but they are within allowable limits. (Concrete can withstand compression in the range of 12-50 MPa depending on the concrete class. But concrete has a low tensile capacity and tension should be avoided as it will lead to cracks) (Bochnak, 2020).The variation in the displacement values is not linear and this is because, the grout curtains are of same area but they are placed at different points along the RCC-foundation interface. Their location along the RCC-foundation interface has an important effect on stress concentration around the grout curtains, stress distribution in the foundation and lowering of displacement values along the RCC-foundation interface and the bedrock foundation. It is also observed that displacements in the dam body and different types of stresses have inverse relationship but of different degrees, upon the addition of grout curtains. There might be no specific relationship but of random nature due to different composition of the RCC dam body and the foundation. Also, the placement of grout curtains at different locations cause them to have no specific relationship.

If the values from the displacement analysis of Longtan dam and Diamer Basha dam for their maximum water level conditions are compared (for the conditions of 2 grout curtains being part of the structure of two dams), it is observed that for Y direction, the displacements are having value up to 4 cm in the top of the dam section for Longtan dam and displacement of 50 cm in the top of the Diamer Basha dam. These values of Longtan dam are showing larger displacement but if the displacements are put in proportion to the large dam dimension (216 meters), they are insignificant (Bochnak, 2020). Same applies for the case of Diamer Basha dam too. The dam is 272 meters tall and 209 meters wide. In this scenario, displacement in the Y direction which varies from [-50, -450 cm], is the large value. But, the displacements are reduced to the insignificant range of [-60, -5 cm], when 4 grout curtains are part of the dam's geometry, as the dam is having greater height than the Longtan dam.

Table 4.3 Stress and displacement values for different conditions of grout curtains

Parameter	**Dam geometry having 1 grout curtain**	**Dam geometry having 2 grout curtains**	**Dam geometry having 3 grout curtains**	**Dam geometry having 4 grout curtains**
Displacement-X direction (cm)	[-50, 220]	[-120, 100]	[-20, 85]	[-10, 35]
Displacement-Y direction (cm)	[-330, -45]	[-450,-50]	[-140, -15]	[-50, -5]
Displacement-XY direction (cm)	[40,390]	[0,400]	[10, 140]	[0, 55]
Shear stress (MPa)	[0,4]	[0,5]	[0, 7.5]	[0, 8.5]
Total stress, X-direction (MPa)	[-2, 8]	[-1, 5.5]	[-8, 16]	[-4, 16]
Total stress, Y-direction (MPa)	[-0.75, 9]	[-2, 10]	[-1.5, 14]	[-2, 16]
Total stress, Z-direction (MPa)	[-0.2,3]	[-0.2,3]	[-0.4, 5.5]	[-0.5, 6.5]
Total maximal stress (MPa)	[2, 12]	[0, 12]	[0, 22]	[0, 26]
Total minimal stress (MPa)	[-2.5, 3.5]	[-2.5, 3.5]	[-4, 6.5]	[-4, 8]

Chapter # 5

5. Conclusions and recommendations:

5.1. Conclusions:

- For the 3 different cases (steady state seepage condition), variation of water level is occurring only at the upstream face of the dam and downstream water level remains constant. When pore water pressure values obtained as results from analysis done, of the dam geometrical section are compared, the result shows that pore water pressure varies greatly as the water level on upstream changes. In addition, there is uniformity in pore water pressurevalues, which is obtained in case of maximum water level for normal working conditions and check level for flood conditions which means that insignificant effect observed for small variation in water level.
- In case of pressure head, for the case of total water head of 160 m, greater variation exists within the dam body and the foundation. However, for all cases, maximum pressure head exists at the upstream face or within the portion adjacent to the upstream face and minimum pressure head exists at the downstream edge of the foundation.
- The comparison of post construction, steady state seepage and rapid draw down conditions shows that it is obvious that greater value of seepage is obtained in case of post construction case where check flood level is 267.7 m on U/S with 0 m on D/S. This means, from the seepage perspective, flood condition will be the worst condition. In addition, seepage values vary for different cases but the order of seepage (e^{-12}) is same. This is due to the reason of homogeneity of material for the dam body (RCC). This leads to uniformity in the trend of seepage values for RCC having different water levels.

- For the RCC-foundation interface, seepage is maximum at heel due to heterogeneity of materials, RCC and foundation bedrock. Although both have different permeability but the high permeability of bedrock, foundation is dominant here, because of seepage in downward direction, causing to have high value of seepage there and making it a critical section. In addition, there exists greater value of suction pressure, which might make the toe section more vulnerable to cracks than the remaining section. However, seepage velocity for toe [$1.10e^{-7}$ m/sec (X-direction), $-1.16e^{-7}$ m/sec (Y-direction)] and heel [$1.13e^{-7}$ m/sec (X-direction), $1.46e^{-7}$ m/sec (Y-direction) are within prescribed limits (0, 0, 1-6m/sec). This shows that safety measures are not needed to be installed at toe and heel but for additional safety purpose, they can be recommended.
- As for the limit of seepage velocity values, which might cause erosion and harmful scour for loose earth and rocks, is concerned, the limits are (0, 0, 1-6 m/sec). From the seepage analysis done, maximum value found for the bedrock foundation is for the case having maximum water level correspondent to flood level, and here the seepage velocity in X direction is $4.47e^{-8}$ m/sec and for Y direction, it is $4.69e^{-8}$ m/sec. Hence, seepage values are within prescribed limits.
- For the seepage of the bedrock foundation, this can be observed that pore water pressure is varying from upstream to downstream, following the mass-balance approach at different nodes of the elements. This mass-balance approach is applied as part of finite element modelling in SEEP/W. Although irregularity exists but the results show the smooth flow nets exist here. Seepage of foundation is found to be higher than the RCC dam body because of the obvious reasons of higher permeability of bedrock foundation.
- As for as hydraulic gradients in X and Y directions are concerned, they show the hydraulic energy state in the element which is present because of pore water pressure. For the curved surface cases, there exists a gradient concentration at the point of maximum curvature due to the occurrence of gradients in both the X and Y directions, which create an overall higher hydraulic energy state in the element. In addition, for the gradient in Y direction, both curvature change and pore-water

pressure are important and for the X-direction gradient, pore-water pressure is of more significance.

- From the displacement analysis, it is shown that negative displacements are more in the Y-direction which tries to overturn the structure (-140 cm for the case of 3 grout curtains and -50 cm for the case of 4 grout curtains). This is because of same water level on both U/S and D/S sides of structure, due to which uplift pressure is playing important role. The displacements, in comparison to dam dimensions, are not much large.
- Concrete has the capacity to resist 12-50 MPa compression depending on its class but small tension values can be resisted by it. For minimum water level working conditions, the maximum stress has higher value of 26 MPa (compression) and minimum stress has lowest value of 0 MPa. This shows that stresses are within acceptable range. As for maximum water level working conditions are concerned, maximum stress has value of 26 MPa (compression) and minimum stress has value of 0 MPa. Here, compression stress has high value but it is within acceptable range and tensional stress has low value.
- The high stress values in the toe and heel corners of the dam might be because of stress singularities. Nevertheless, these are of compressive in nature and are bearable because of the high strength of the bedrock foundation.
- The values of stresses (shear stress, stress in X direction, maximum total stress and minimum total stress) are more in case of U/S water level of 260 m compared with the stresses found in case of U/S water level of 160 m. However, displacements in Y and XY directions are not much changed as compared with the displacements in X direction.
- If the case of stress analysis for maximum water level of dam without grout curtains is concerned, displacements increase considerably but stresses also decrease significantly (Positive displacement in Y-direction is increased by 30%, maximum total stresses are decreased by 20%). This is due to the reason stress concentration and stress irregularities which usually take place at the corners because of installment of grout curtains, is now dissipated largely. As for as

increase in displacement is concerned, grout curtains are installed up to a specific height within the RCC dam body, down to the specific height within the bedrock foundation and they act to provide bonding forces for the two regions of the dam. If no grout curtains are there, bonding forces will not be there and the displacements increase to a high value.

5.2. Recommendations:

1) Although there are minor chances of seepage in the RCC dam body and bedrock foundation but seepage is more at the foundation-RCC interface. This leads to the greater vulnerability of RCC-foundation interface for uplift pressure and cracks in the RCC or rock foundation. However, seepage values are within prescribed limits, but the uplift pressure might have more value depending on complexity of analysis of bedrock foundation and uncertainty in the values of parameters of bedrock foundation.
2) The heel and toe sections are specifically vulnerable having greater seepage than the rest of the RCC-foundation interface portion. This makes the heel more vulnerable to uplift due to maximum value of seepage encountered there, and possibility of cracks at the toe due to the maximum suction of pore water pressure.
3) Any disturbance to the toe or heel sections might cause the failure of the RCC structure, which is considered as one of the catastrophic failures of civil engineering structures as these structures are meant to stand for the safety of downstream communities and areas from flood damage. Even minor issues influencing the stability of dam is dangerous for the lives of people. However, as seepage values found from analysis done are within prescribed limits for rocks, hence safety measures are not needed, although grout curtains can be installed near toe and heel for additional safety purposes.
4) As the method of construction employed for RCC dam is thin-layer construction, there are more chances of seepage in the RCC dam body due to this construction method. For prevention of seepage in the RCC body, impervious layer of grout-

enriched concrete is needed to be installed at the upstream face of the RCC dam. This is usually done in ordinary practice to prevent the minor chances of seepage in the RCC body.

5) The seepage safety measures usually installed in case of RCC dams are on either upstream face or grout curtains. Both measures can be opted for, depending upon economy and safety requirements.

6) In conventional application, usage of grout-enriched concrete at the upstream face of the dam greatly reduces the chances of seepage in the dam and the possibility of cracks at the base of the dam. Same measures needed to be applied for Diamer Basha dam.

7) Grout curtains are recommended to be installed at the interface or up to specific height within the RCC dam body down to the bedrock foundation, to prevent large displacements of the dam.

8) The design for both seepage and displacement analysis as based on consultants' studies and drawings, is found to be reliable and it requires no safety measures but for additional safety, installment of grout curtains at various locations, along the RCC-foundation interface will greatly help in mitigating the chances of even minor seepage and stress singularities found at the toe and the heel. It is also observed that there are complications involved in the comprehension of seepage patterns in the foundation, and in operational stages, foundation should be carefully observed for any irregularity and unique patterns of seepage. Here, the addition of grout curtains of specific sizes at specific locations across the RCC-foundation interface is unique in its aspect as they are not part of dam' geometrical section. Their inclusion in the design impacts the stress distribution and deformations across the section.

Chapter # 6

6. References:

1) Ali, Wajahat, Iqtidar Hussain, Haroon Rashid, and Abdul Nasir. 2020. "Development of Eia Guidelines of Significant Factors For Diamer Basha Dam Gilgit Baltistan." *Pakistan Journal of Geology* 4 (1): 43–55. https://doi.org/10.2478/pjg-2020-0006.
2) Baghdady, Shayma Al, and Linnea Khan. 2018. *Designing Roller Compacted Concrete (RCC) Dams*.
3) Banthia, By Nemkumar, Michel Pigeon, Jaques Marchand, and Jean Boisvert. 1992. "Permeability of Roller Compacted Concrete" 4 (1): 27–40.
4) Bochnak, P L A, and M E Correa Saracco. 2020. "Design of RCC Gravity Dam and FEM Modelling in GeoStudio-Longtan Dam." *Tvvr20/5001*.
5) Cruess, Richard L., Sylvia R. Cruess, J. Donald Boudreau, Linda Snell, and Yvonne Steinert. 2014. "Reframing Medical Education to Support Professional Identity Formation." *Academic Medicine* 89 (11): 1446–51. https://doi.org/10.1097/ACM.0000000000000427.
6) Geo-slope. (2018). *Seepage modelling with SEEP/W.* Geostudio Intl Ltd.
7) Graham, Wayne. 1999. "A Procedure for Estimating Loss of Life Caused by Dam Failure." *Sedimentation & River Hydraulics*, no. September: 43.
8) Habib, Ahed, Ausamah Al Houri, Maan Habib, Ahmed Elzokra, and Umut Yildirim. 2021. "Structural Performance and Finite Element Modeling of Roller Compacted Concrete Dams: A Review." *Latin American Journal of Solids and Structures* 18 (4): 1–18. https://doi.org/10.1590/1679-78256467.
9) Imran Arshad, Engr, and M M Babar. 2014. "Comparison of SEEP/W Simulations with Field Observations for Seepage Analysis through an Earthen Dam (Case Study: Hub Dam - Pakistan)." *International Journal of Research (IJR)* 1 (7): 57–70.
10) Kamanbedast, A., and A. Delvari. 2012. "Analysis of Earth Dam: Seepage and

Stability Using Ansys and Geo-Studio Software." *World Applied Sciences Journal* 17 (9): 1087–94.

11) Liu, Jian, Xia Ting Feng, and Xiu Li Ding. 2003. "Stability Assessment of the Three-Gorges Dam Foundation, China, Using Physical and Numerical Modeling-Part II: Numerical Modeling." *International Journal of Rock Mechanics and Mining Sciences* 40 (5): 633–52. https://doi.org/10.1016/S1365-1609(03)00056-X.

12) Liu, Jian, Xia Ting Feng, Xiu Li Ding, Jie Zhang, and Deng Ming Yue. 2003. "Stability Assessment of the Three-Gorges Dam Foundation, China, Using Physical and Numerical Modeling-Part I: Physical Model Tests." *International Journal of Rock Mechanics and Mining Sciences* 40 (5): 609–31. https://doi.org/10.1016/S1365-1609(03)00055-8.

13) Omofunmi, O, J Kolo, A Oladipo, P Diabana, and A Ojo. 2017. "A Review on Effects and Control of Seepage through Earth-Fill Dam." *Current Journal of Applied Science and Technology* 22 (5): 1–11. https://doi.org/10.9734/cjast/2017/28538.

14) Portella, K. F., Baron, O., Soares, M. A., Elias, M. M., Borges, A. C. 2018. "Three Years of Physicochemical Seepage Water Analysis from Jordao River Dispersion RCC First Barazilian Dam: Diagnose. In Roller Compacted Concrete Dams." *Routledge*, 1179–83.

15) Ratnayaka, Don D., Malcolm J. Brandt, and K. Michael Johnson. 2009. "Dams, Reservoirs and River Intakes." In *Water Supply*, 149–93. Elsevier. https://doi.org/10.1016/B978-0-7506-6843-9.00013-5.

16) Soares, M. A., Levis, P., Seara, R. W., Ferreira, E. S., Terres, J. F. 2018. "Seepage and Treatment of Caracks in Salto Caxias Dam. In Roller Compacted Concrete Dams." *Routledge*, 1185–91.

17) Thesis, Doctoral, and Economic Sciences. 2020. "Deformation Behaviour of a Concrete Gravity Dam Based on Monitoring Data and Numerical Simulation," no. December.

18) USACE. 1986. "Engineering and Design - Seepage Analysis and Control for

Dams." *Em-1110-2-1901*, 392.

19) Yao, Huiqin, and Dongmei Liu. 2021. "Study on Seepage Monitoring and Analysis of SL Gravity Dam." *2021 7th International Conference on Hydraulic and Civil Engineering and Smart Water Conservancy and Intelligent Disaster Reduction Forum, ICHCE and SWIDR 2021*, 1475–78. https://doi.org/10.1109/ICHCESWIDR54323.2021.9656287.
20) Zafar, S. 1997. "Strength and Hydraulic Conductivity Characteristics of Roller Compacted Concrete."
21) Zhang, Kailai, Liqun Xu, Liting Qiu, Jiacheng Tan, Chao Yang, and Kai Zhang. 2021. "Numerical Analysis of Concrete Gravity Dam Seepage Characteristics Evolution Considering the Calcium Leaching Effect." *Advances in Civil Engineering* 2021. https://doi.org/10.1155/2021/9042863.