SEEPAGE-INDUCED PIPING RISK AT THE DOWNSTREAM TOE: A STABILITY AND VULNERABILITY ASSESSMENT OF THE BOHOL QAWLO CFRD, SOMALILAND

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PRESENTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER'S SCIENCE IN WATER RESOURCES ENGINEERING (SPECIALIZATION IN HYDRUALIC ENGINEERING)

SCHOOL OF GRADUATE STUDIES
ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

JANUARY, 2026
ADAMA, ETHIOPIA

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By

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A THESIS SUBMITTED TO THE DEPARTMENT OF
WATER RESOURCES ENGINEERING, COLLEGE OF CIVIL ENGINEERING AND ARCHITECTURE

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DECLARATION

I hereby declare that this thesis, entitled "Seepage-induced piping risk at the downstream toe: a stability and vulnerability assessment of the Bohol qawlo CFRD, Somaliland, "is the result of my own original research. It has not been submitted, in whole or in part, for any degree or qualification at any other institution. All sources of information have been appropriately acknowledged by means of citation.

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Name of student	Signature	Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis "Seepage-induced piping risk at the downstream toe: a stability and vulnerability assessment of the Bohol qawlo CFRD, Somaliland, "Prepared under my guidance by Abdisalam Yousuf, submitted in partial fulfillment of the requirements for the degree of Masters of Science in the Department of Water Resources Engineering (Specialization in hydraulic engineering)

Therefore, I recommend the submission of a revised version of the thesis to the department following the applicable procedures

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APPROVAL PAGE

I, the advisor of the thesis entitled “Seepage-induced piping risk at the downstream toe: a stability and vulnerability assessment of the Bohol qawlo CFRD, Somaliland,” and developed by Abdisalam Yousuf, hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Abdisalam Yousuf, have read and evaluated the thesis entitled “Seepage-induced piping risk at the downstream toe: a stability and vulnerability assessment of the Bohol qawlo CFRD, Somaliland,” “and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirements of the degree of Master of Science in the Department of Water Resources Engineering, College of Civil Engineering and Architecture.

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ACKNOWLEDGEMENT

All praise and deepest gratitude are due to Allah, the Most Gracious, and the Most Merciful, for His boundless benevolence in bestowing upon me the sound health, intellectual strength, and sustained perseverance to bring this lengthy and rigorous research endeavor to a successful fruition. I extend my most profound and sincere appreciation to my esteemed major advisor, Dr. Bahru Mekuria, for his invaluable guidance, scholarly dedication, and unwavering support. His critical insights into the geotechnical modeling, timely feedback, and professional mentorship have truly been the cornerstone that shaped the direction, methodology, and final quality of this thesis, profoundly contributing to my academic and professional development. My sincere thanks also go to the MECCO Construction Company for generously providing the necessary technical data and specifications used as the foundation for this critical analysis. I am eternally and deeply indebted to my beloved family, my mother, siblings, and my entire extended circle or their unconditional love, endless encouragement, patience, and steadfast belief in me; their prayers and significant sacrifices have been a constant, non-negotiable source of motivation and strength throughout this challenging journey. Finally, I humbly acknowledge the personal determination and resilience required to navigate the complexities of this work, recognizing the hard work invested as a significant and rewarding scholarly achievement.

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LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
AHP	Analytic Hierarchy Process
ASTU	Adama Science and Technology University
CFRD	Concrete-faced Rock-fill Dam
D/S	Downstream
DEM	Digital Elevation Model
ERT	Electrical Resistivity Tomography
FOS	Factor of Safety
FSL	Full Supply Level
GIS	Geographic Information Systems
MCDM	Multi-Criteria Decision Making
MECCO	Modern Enterprise and Construction Company
OPS	Office of Postgraduate Studies
PGA	Peak Ground Acceleration
QGIS	Quantum Geographic Information System
RCC	Reinforced Concrete Cement
SGCS	School Graduate Committee
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
THA	Time History Analysis
U/S	Upstream
USACE U.S.	Army Corps of Engineers
USBRU.S.	Bureau of Reclamation
VES	Vertical Electrical Sounding
VLF-EM	Very Low Frequency Electromagnetic
NWL	Normal Water Level
L. E. M.	Limit Equilibrium Method
FEM	Finite Element Method
PWP	Pore Water Pressure
CFRM	Concrete-Faced Rockfill Dam

ABSTRACT

Water scarcity is a persistent challenge in arid regions like Somaliland, necessitating the development of vital infrastructure such as the Bohol Qawlo Embankment Dam in the Gabiley Region. However, constructing hydraulic structures on permeable sandy colluvium foundations introduces significant geotechnical risks, particularly regarding seepage control and internal erosion. This study evaluates the performance of the Bohol Qawlo Concrete-Faced Rock fill Dam (CFRD) by investigating its seepage behavior, slope stability, and load-deformation characteristics under critical loading conditions. The research utilized the GeoStudio 2018 numerical modeling suite, employing the Finite Element Method (SEEP/W and SIGMA/W) and the Limit Equilibrium Method (SLOPE/W).

The seepage analysis confirmed that while the upstream concrete face effectively serves as an impermeable barrier, a critical hydraulic vulnerability exists at the downstream toe. A peak seepage flux of 2.4× 10-4 m3/sec/m2 was recorded at the interface between the dam body and the colluvium foundation. In the absence of a transition filter, this high-velocity flux presents a high risk of particle migration, internal erosion (piping), and progressive foundation washout. Conversely, the structural slope stability analysis demonstrated robust performance, with the Factor of Safety (FOS) for the downstream slope calculated at 1.490 for End-of-Construction, 1.731 for Long-Term Steady State, and 1.477 under seismic loading. These values significantly exceed the minimum safety criteria established by the U.S. Army Corps of Engineers (USACE). Deformation analysis further revealed high structural stiffness, with a maximum vertical settlement of only 0.024 m (0.15% of the dam height). The study concludes that while the dam is mechanically stable, immediate remedial measures, specifically an engineered toe drain with an inverted filter, are required to mitigate hydraulic risks and ensure long-term sustainability.

***Keywords**: Seepage Analysis, Slope Stability, Internal Erosion (Piping), GeoStudio, Factor of Safety, CFRD.*

CHAPTER ONE: INTRODUCTION

1.1. Background

Embankment dams are among the most widely used hydraulic structures for water resource management, serving essential purposes such as water supply, irrigation, flood control, and energy generation. Globally, embankment dams represent nearly 78% of all dams and are generally constructed using natural earth or rock materials Divya et al., (2023). The two most common types are earth-fill dams, composed of compacted soil, and rockfill dams, which utilize rock fragments to form the structure (Wu et al., 2024).

In Somaliland, water scarcity remains a critical challenge, particularly for pastoral and agro-pastoral communities that are highly vulnerable to recurrent droughts. Regions such as Sanaag, Sool, and Togdheer frequently experience severe water shortages. These droughts, intensified by climate change, cause crop failures, reduce grazing land, and undermine food security Abdulkadir, (2017). Addressing these challenges requires improved water resource management and reliable drought-mitigation strategies.

Historically, water scarcity in Somaliland has been managed through traditional systems such as hafir dams and deep wells. More recently, the construction of large-scale Concrete-Faced Rockfill Dams (CFRDs) marks a major step forward in the country's water infrastructure. As these structures are relatively new to the region, it is crucial to evaluate their performance, particularly their stability and resistance to seepage.

The Gabiley region in western Somaliland offers an important case study. It has an estimated population of 146,527 and a land area of 4,328 km² (UNFPA, 2019). The main sources of livelihood are agriculture, livestock rearing, and small businesses. About 37% of the land is suitable for rain-fed farming, with cereals being the dominant crops, while sheep and goats are the most important livestock (Abdulkadir, 2017).

However, Gabiley experiences frequent droughts, with major events reported in 1998, 2002, 2009, 2015, and 2017 (Omar et al., 2023). Increasing aridity and reduced rainfall further degrade local ecosystems and water resources (Chen et al., 2024). While rainwater harvesting systems have been introduced to mitigate scarcity, the sandy and loamy soils in the region limit water retention Omer & Tekile, (2024).

To address these challenges, the Bohol Qawlo Embankment Dam was constructed in 2020 near the Ilaaja seasonal stream on the outskirts of Gabiley town. According to the project engineer interview, (2020), the dam has a reservoir area of about 1 km² and a storage capacity of 1 million cubic meters. This dam plays a vital role in supplying water for domestic use, livestock, and agriculture. By conserving rainwater that would otherwise be lost as runoff, it improves water availability and strengthens community resilience against drought.

1.2. Statement of the Problem

The Bohol Qawlo Concrete-Faced Rockfill Dam (CFRD), a critical water resource for the Gabiley Region in Somaliland, faces significant geotechnical risks due to its construction on a highly permeable sandy colluvium foundation. While the upstream concrete face effectively blocks reservoir water from entering the dam body, numerical analysis reveals a critical hydraulic vulnerability at the downstream toe.

Without immediate intervention and the installation of an engineered toe drain with an inverted filter, the Bohol Qawlo Dam is at high risk of particle migration, internal erosion (piping), and progressive foundation washout. This research is therefore essential to quantify these specific hydraulic forces and provide the technical basis for remedial measures to prevent catastrophic failure and ensure the dam's long-term sustainability

1.3. General Objective

The general objective of this study is to evaluate the seepage behavior, slope stability, and load-deformation characteristics of the Bohol Qawlo Embankment Dam.

1.3.1. Specific Objectives

The specific objectives of this research are outlined below to address the research problem:

- To analyze the steady-state seepage behavior of the Bohol Qawlo dam.
- To evaluate the slope stability of the upstream and downstream slopes under critical static loading conditions, including End-of-Construction and Long-Term Steady State seepage and Stability under Seismic Conditions.
- To estimate the load-deformation behavior of the dam, specifically quantifying vertical settlement and horizontal displacement.

1.4. Research Questions

The following research questions are set to address specific objectives of the research:

- What are the characteristics of the phreatic surface and hydraulic gradients within the dam, and is the seepage flux at the downstream toe safely contained to prevent internal erosion?

- Does the Factor of Safety (FOS) for the upstream and downstream slopes meet the USACE minimum requirements under End-of-Construction and Steady-State conditions?
- Are the predicted vertical settlements and horizontal spreading of the dam body and sandy foundation minimal and uniform enough to prevent differential cracking or structural failure?
- What remedial techniques can be recommended to ensure the safety of the Bohol Qawlo Dam is maintained to serve its intended purpose?

1.5. Significance of the Study

This research is crucial for the Gabiley region of Somaliland, due to the serious issue of water shortages where capturing rainfall could significantly alleviate drought conditions. The Bohol Qawlo Dam is critical infrastructure for water storage; thus, the structural safety of the dam must be guaranteed to avoid catastrophic failure that could endanger lives and livelihoods. By confirming the stability of the dam on a sandy foundation, this research supports the sustainability of the water supply for agriculture and domestic use in the area.

From a geotechnical perspective, this research addresses specific problems related to the construction of embankment dams on sandy soils subject to high permeability and internal erosion. By using numerical modeling—specifically GeoStudio—to analyze seepage flux, slope stability, and load-deformation behavior, this research aims to bridge the gap between theoretical soil mechanics and its practical application. It provides insights into the performance of Concrete-Faced Rockfill Dams (CFRD) on permeable foundations and presents data that could guide the design of cost-effective and safe hydraulic structures in similar arid environments.

Furthermore, this study provides an academic foundation for future work on the long-term performance of embankment dams in Somaliland. The results regarding settlement behavior and phreatic line characteristics enable a better understanding of soil-structure interaction. Additionally, the outcome of this investigation contributes to local regulatory frameworks and policy decisions regarding dam safety guidelines and maintenance protocols for infrastructure built on challenging soil conditions.

1.6. Scope of the Study

The research work is geographically limited to the study of the Bohol Qawlo Embankment Dam in the Gabiley Region of Somaliland, examining its geotechnical performance on a sandy soil foundation. It employs the GeoStudio 2018 software suite to analyze steady-state seepage behavior for the determination of the phreatic line and flux; slope stability through the Limit Equilibrium Method under conditions of both End-of-Construction and Long-Term Steady State loading; and load-deformation characteristics necessary to estimate vertical settlement and horizontal displacement. As such, the analysis focuses solely on static loading and hydraulic performance, while dynamic seismic considerations are omitted.

1.7. Limitations of the Study

Although this study benefits from utilizing primary geotechnical data and specific material properties obtained from the construction company, it is subject to some limitations associated with numerical modeling. First, while the input parameters have been prepared based on actual site investigations, the analysis in GeoStudio 2018 assumes idealized soil behavior and continuity, which may not fully capture every localized heterogeneity within the complex foundation. Second, the investigation is strictly limited to static loading scenarios—namely seepage, slope stability, and load-deformation—and excludes seismic analysis; hence, the performance of the dam under dynamic earthquake loading conditions falls outside the scope of this research. Finally, the study focuses on the geotechnical safety of the structure and does not extend to long-term monitoring of piping erosion mechanics or economic feasibility assessments.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction to Embankment Dams

Embankment dams are broadly used hydraulic structures that are vital in ensuring sustainable water resource management; they are mainly designed for water storage, regulation of river flow, and reduction of flood risks. According to Mattias, (2010), these structures are vital in supporting agriculture through irrigation, domestic water supply, and renewable energy through hydroelectric power generation.

(Wu et al, 2024) note that despite these important benefits, embankment dams are usually associated with significant structural hazards. For instance, they note that failures due to seepage or poor foundation conditions have been known to cause catastrophic downstream consequences. On the other hand, Sainov, (2020) postulates that continual innovations in geotechnical engineering and building materials have played a crucial role in improving the safety and efficiency of such structures, hence lowering potential dangers. It is from this dual reality of essential utility set against geotechnical hazard that the Bohol Qawlo Dam in Gabiley, Somaliland, needs to be assessed, focusing on opportunities and vulnerabilities resulting from its sandy soil foundation.

2.2 Types of Embankment Dams

Embankment dams are broadly classified based on the materials used and their internal structural arrangement. The two most common categories are earth fill dams and rock fill dams, both of which are widely applied due to their adaptability to different site conditions and the availability of construction materials. The choice of type is typically influenced by local topography, geology, material availability, and hydraulic requirements (U.S. Bureau of Reclamation (USBR, 2014).

2.2.1 Earth Fill Dams

Earth fill dams are primarily constructed using soil materials, usually compacted in layers to form a stable structure. They are further divided into three main subtypes depending on how impervious and pervious zones are arranged:

Diaphragm Embankments: these consist mostly of pervious materials (such as sand, gravel, or rock), with a thin diaphragm of impermeable material serving as a water barrier. The diaphragm can be placed on the upstream face or internally within the core. Materials used for diaphragms include asphaltic concrete, reinforced concrete, compacted earth (thin core), metal, or geomembranes. While effective, internal diaphragms pose inspection and repair challenges if ruptures occur due to settlement or material flaws (USBR, 2014).

Homogeneous Earth Fill dams: In this type, the embankment is constructed primarily from a single, relatively impervious material, often clay or fine-grained soils. Homogeneous dams are simpler to design and build but may require drainage blankets, relief wells, or horizontal filters to address seepage issues and ensure long-term stability (Silveira, 2022).

Zoned Earth Fill dams incorporate an impervious central core, commonly clay, flanked by shells of more permeable material such as sand, gravel, or rock fill. This zoning reduces seepage while providing additional structural strength. The central core acts as the primary water barrier, while the outer shells resist external forces and protect against erosion. This type has become the most widely used configuration due to its balance between safety and economy (USBR, 2014).

2.2.2 Rock Fill Dams

Rock fill dams rely primarily on rock fragments as their main structural material. These rocks may be dumped or compacted in thin layers, providing a stable and highly permeable shell. To ensure water tightness, an impermeable membrane or core is included. Rock fill dams are classified according to the placement of this membrane:

Central Core Rockfill Dams

These include a vertical or nearly vertical impermeable core, usually made of clay, asphaltic concrete, or reinforced concrete, located centrally within the rockfill mass. The core ensures seepage control, while the rockfill shoulders provide stability and resistance against external loads.

- Sloping Core Rockfill Dams

In this type, the impermeable core is inclined towards the upstream side. Sloping cores simplify construction sequences in some cases and are chosen where materials or topographic conditions favor such geometry. Their performance is comparable to central cores, and the selection is often based on economic considerations and foundation conditions (USBR, 2014).

- Upstream Membrane (Decked) Rockfill Dams

Here, the impermeable element is placed on the upstream slope of the dam. Materials used include reinforced concrete, asphaltic concrete, geomembranes, or compacted clay. This arrangement is particularly advantageous in regions with seismic activity, as the flexible membrane accommodates settlement and deformation without compromising impermeability (USBR, 2014).

Both earth fill and rock fill dams offer unique benefits. Earth fill dams are more common in areas with abundant soil resources and are generally economical for moderate heights. However, they require careful seepage control measures. Rock fill dams, by contrast, provide high stability, better performance in seismic conditions, and adaptability in steep valleys where large quantities of rock are available. Their main limitation lies in construction cost, particularly when impervious membranes or high-quality rock are scarce (USBR, 2014).

For the Bohol-Qawlo Embankment Dam case study, a Concrete Faced Rockfill Dam (CFRD) utilizing locally available material is proposed.

2.3 Historical Embankment Dam Failures

Analyzing historical dam failures offers vital lessons regarding the mechanisms that threaten structural integrity, with overtopping, seepage, and slope instability appearing as the most recurrent causes Novak et al., (2007). These events underscore the necessity for rigorous site investigation and robust design.

Internal erosion, or piping, is a catastrophic failure mode. The collapse of the Teton Dam in 1976 is a prime example, where seepage through a fissured rock foundation washed away fine materials during the initial filling, causing a rapid breach (Gebeyehu, 2014; U.S. Army Corps of Engineers (USACE, 2004). Similarly, the 1963 Baldwin Hills Dam failure was caused by foundation erosion along a geological fault, illustrating how progressive leakage can lead to sudden disaster (USACE, 2004). The Puddingstone Dam failure further highlights the danger of material migration, where fine core material eroded into the coarser downstream shell due to inadequate filter design Mekonnen, (2017).

Overtopping is another prevalent cause of failure, typically resulting from insufficient spillway capacity. The 1889 South Fork Dam disaster, which triggered the Johnstown Flood, occurred when extreme rainfall overwhelmed a blocked spillway, eroding the downstream face (Novak et al., 2007). More recently, the 1972 Buffalo Creek Dam failure involved the overtopping of a poorly engineered coal waste embankment, reinforcing the need for stringent hydraulic standards (USACE, 2004).

Finally, geotechnical instability remains a significant risk. The massive slide at Fort Peck Dam in 1938, caused by the weak shear strength of the shale foundation, served as a pivotal event that advanced the understanding of soil mechanics in dam engineering (USACE, 2004). Collectively, these historical cases mandate the comprehensive evaluation of hydraulic capacity and geotechnical stability in all dam projects.

2.4 Soil Mechanics and Properties

Soil mechanics provides the theoretical framework for understanding how soil behaves under mechanical stress, a critical factor in geotechnical engineering, and environmental management. This discipline examines how variables such as composition, moisture content, and pore water pressure influence material performance.

A soil's mechanical response—specifically its deformation and strength—is heavily dependent on its hydration state. Berli and Hallett, (2023) that soils exhibit a rheological shift based on moisture levels, transitioning from elastic behavior in dry states to viscous flow when saturated. To quantify this stability, engineers rely on fundamental parameters including Young's modulus, Poisson's ratio, and shear strength (Kioko, 2023).

In geotechnical contexts, soils often exist as heterogeneous mixtures. For example, in soil–rock mixtures, the proportion of rock content significantly alters mechanical behavior; higher rock content can ironically reduce uniaxial compressive strength by introducing weak interfaces. Wu et al. (2024) highlight that the soil–rock interface is a critical zone for crack propagation, directly affecting overall structural stability. Furthermore, pore water pressure acts as a destabilizing force, particularly in loess soils where increased pressure induces microstructural collapse. Finally, while mechanical properties are paramount, Khelalfa and Khelalfa (2024) argue that biological interactions within the soil matrix also merit attention, as they influence ecosystem stability and plant growth.

2.5 Performance of Embankment Dams in Different Soil Conditions

The structural performance of embankment dams is intrinsically linked to the engineering properties of the soils used in their zones. The choice of material dictates the dam's stability, seepage control, and resilience against static and seismic loading.

2.5.1 Fine-Grained Soils (Cores)

Fine-grained soils, particularly clays, are the standard material for impervious cores due to their low permeability. However, these materials present challenges regarding shear strength and compressibility. If not compacted correctly, clay cores are susceptible to differential settlement, which can lead to transverse cracking and dangerous internal erosion (USACE, 2004).

2.5.2 Coarse-Grained Soils (Shells)

Conversely, coarse-grained materials like sands and gravels are utilized for the outer shells to provide structural stability and high shear strength. While these materials mitigate slope failure, their high permeability creates a risk of piping—the internal migration of fine particles. To prevent this, Novak et al, (2007) emphasize the necessity of properly graded filters and drainage layers. Without these defenses, sandy soils are highly vulnerable to piping failures, which Gebeyehu, (2014) identifies as a leading cause of dam breaches.

The contrast in soil behavior is most evident during loading events and hydraulic analysis:

- Seepage: There is a stark difference in hydraulic conductivity between material types. (Iswanto et al.2022) found that while sand may allow seepage discharges around 1.90 × 10-3, clay restricts flow to approximately 1.47 × 10-9. This disparity underscores why zoning is essential for managing elevated seepage rates.
- Seismic Activity: Under dynamic seismic loading, sand and gravel embankments are prone to settlement and liquefaction due to their low cohesion and high porosity. In contrast, cohesive clay soils generally exhibit reduced compressibility during seismic events, provided that excess pore water pressures can be dissipated effectively (Khan & Seyedi, 2023).

2.6 Seepage in Embankment Dams

The structural integrity and operational safety of embankment dams are fundamentally dependent on effective seepage analysis. Uncontrolled seepage can lead to internal erosion and slope instability; therefore, modern engineering combines non-invasive geophysical investigations with advanced numerical modeling to identify vulnerabilities and evaluate the efficiency of remedial measures.

Recent research highlights the efficacy of geophysical methods in detecting subsurface anomalies without disturbing the dam structure. For example, Akinlabi and Olanrewaju, (2024) successfully utilized Very Low Frequency Electromagnetic (VLF-EM) methods and Vertical Electrical Sounding (VES) at the Asejire Dam to delineate conductive zones indicative of active seepage. Similarly, multi-method approaches have proven valuable; Adetokunbo et al. (2024) employed Electrical Resistivity Tomography (ERT), integrated with self-potential and surface wave analysis, at the Chimney Rock Dam. Their study revealed that low-resistivity zones correlated strongly with high moisture content, effectively mapping potential seepage pathways and providing a comprehensive assessment of the dam's internal structure.

Beyond detection, numerical simulation is critical for predicting seepage behavior and validating safety controls. Finite Element Methods (FEM) allow engineers to simulate complex hydraulic scenarios and the effectiveness of barriers. Nikrou and Pirboudaghi (2024) demonstrated this through a study of the Sahand Dam, where FEM analysis confirmed that the implementation of an upstream clay blanket significantly curtailed seepage discharge rates. Furthermore, software specifically designed for geotechnical analysis, such as GeoStudio, remains a standard for compliance verification. Kuntjoro et al. (2023) utilized GeoStudio to calculate seepage discharge and velocity at the Bagong Dam, confirming that the hydraulic parameters remained within safe design limits.

Finally, modeling allows for the assessment of structural resilience under failure scenarios. Research by Rakić et al. (2024) on the Zavoj Dam highlighted the critical role of subsurface barriers, illustrating via simulation how damage to grout curtains directly compromises seepage control and overall stability. These studies collectively underscore that accurate modeling and monitoring are indispensable for maintaining dam safety standards.

2.6.1 Seepage Failure of Embankment Dams

Seepage-induced instability is frequently cited as a primary threat to the long-term safety of embankment dams. The literature emphasizes that seepage generally initiates when water infiltrates the dam body, foundation, or abutments due to defects in critical components such as clay cores, grout curtains, or cutoff walls. Rakić et al. (2024) note that such structural deficiencies create preferential flow paths that can progressively compromise stability.

The physical properties of the construction materials are also pivotal. Numerical modeling indicates that variations in soil composition and permeability drastically alter seepage patterns, with specific soil types exhibiting a higher propensity for leakage Kilit et al., (2023). Field studies, such as those performed on the Arjo-Dedessa Dam, reveal that uncontrolled seepage can dangerously reduce the factor of safety, necessitating remedial actions like grouting or the installation of upstream impermeable blankets (Aga, 2021).

To manage these risks, engineers are increasingly adopting advanced geophysical monitoring. Techniques such as resistivity imaging and Very Low Frequency Electromagnetic (VLF-EM) surveys are utilized to identify potential seepage zones before failure occurs (Akinlabi & Olanrewaju, 2024). Effective management combines this monitoring with proactive measures, such as maintaining reservoir levels below maximum capacity to reduce hydraulic gradients (Kilit et al., 2023). Furthermore, modern computational tools allow for the simulation of design alternatives, as seen in the Way Sekampung Dam project, where design adjustments were optimized to enhance seepage control (Dewi & Nurhasanah, 2022).

2.6.2 Seepage Control on Embankment Dams

Effective seepage control is paramount for maintaining the structural integrity of embankment dams and preventing catastrophic failure. Contemporary engineering relies on a combination of advanced real-time monitoring, field investigation techniques, and physical remedial structures to manage hydraulic flows.

To detect vulnerabilities early, engineers are increasingly adopting high-technology solutions such as Distributed Optical Fiber Seepage Monitoring. This method utilizes a Distributed Temperature Sensing (DTS) system coupled with temperature-seepage models to provide real-time data on internal flow conditions (Li & Yang, 2024). Complementing these high-tech systems are non-destructive field tests. For instance, dye tracer tests are effective for qualitatively and quantitatively pinpointing specific seepage pathways without disturbing the dam structure (Panvalkar et al., 2024). Furthermore, geophysical surveys using VLF-EM and VES continue to be vital for mapping subsurface anomalies and identifying conductive zones associated with seepage (Akinlabi & Olanrewaju, 2024).

When seepage is identified, physical barriers are often required to reduce discharge. The "blanket layer" method has proven particularly effective; a case study at the Telagasari Flood Control Dam demonstrated that implementing an upstream blanket resulted in a 98.97% reduction in drainage discharge (Apriani & Chandra, 2023). To ensure these physical measures are designed correctly, numerical seepage analysis is employed to model pore water pressures and flow patterns. These simulations provide the critical data needed to optimize the design of remedial measures before implementation (Kilit et al., 2023).

2.7 The Stability of Embankment Dams

Stability is the fundamental criterion for dam safety, governed by the interplay of structural geometry, soil mechanics, and hydraulic loading. Instability can result in catastrophic social, economic, and environmental impacts.

- Soil Conditions and Foundation: The foundation material is often the deciding factor in stability. Embankments constructed on soft or compressible soils face risks of low shear strength and excessive settlement. In such cases, ground improvement techniques like preloading or soil stabilization are mandatory to achieve the required bearing capacity (Bhanuchitra et al., 2024). To monitor these risks during construction, predictive tools like the Matsuo stability chart are employed to track lateral displacements and settlement, helping engineers identify potential failure zones in real-time.
- Hydraulic Loading and Aging: Operational stresses, particularly rapid drawdown, pose severe risks to aging infrastructure. A sudden drop in reservoir water levels removes the stabilizing hydrostatic pressure on the upstream slope while pore water pressures inside the dam remain high. The case of the Samarkand Dam illustrates this danger, where rapid drawdown reduced the factor of safety to critical levels. This highlights the need for adaptive operational strategies and updated stability assessments for older structures (Zhussupbekov & Mkilima, 2022).

2.7.1 2D Stability Assessments

2D limit equilibrium methods are widely used due to their computational simplicity. However, they assume a plane-strain condition that often fails to capture complex geometries, such as dams located in narrow valleys or those with heterogeneous soil layering. By neglecting the shear resistance offered by the abutments in the third dimension, 2D analyses typically yield conservative FS values. While this conservatism is safe, it can lead to "over-design," resulting in unnecessary rehabilitation costs and the misallocation of limited safety resources (Quick, 2024; Javankhoshdel et al., 2023).

2.7.2 The Seismic Performance of Embankments

Pseudo-static stability analysis is a conventional limit equilibrium earthquake stability analysis where a horizontal earthquake force is applied to the sliding body in addition to static forces. The additional horizontal force is proportional to the total mass of the sliding body, and the factor of proportionality is denoted as the "earthquake coefficient." This type of analysis is applicable only for dams constructed of materials that do not experience a significant reduction in strength during cyclic loading.

The dense rockfill, which makes up the bulk of the Storvatn Dam, and the asphaltic concrete core are of this type. The permeability of the rock fill and the transition zones is so great that the excess pore pressures generated during cyclic loading dissipate quickly, and no significant accumulation of pore pressures takes place during an earthquake. According to Seed (1979), the acceptable design criterion for a rockfill embankment dam exposed to earthquakes is a pseudo-static factor of safety greater than 1.15 for an earthquake coefficient of 0.1 (for a magnitude 6.5 event), and an earthquake coefficient of 0.15 (for a magnitude 8.25 event).

The pseudo-static load corresponding to a factor of safety of 1.0 is considered the “yield acceleration” of the slope. For many years, seismic coefficients were estimated based on empirical guidelines and codes. Typical values for seismic coefficients used ranged from about 0.05 to about 0.25 (Hynes-Griffin & Franklin, 1984; Kavazanjian et al., 1997; Seed, 1979).

2.8 Evaluate how Settlement Affects the Dam’s Overall Performance and Safety

Settlement significantly impacts a dam's performance and safety, influencing both structural integrity and operational reliability. Understanding settlement behavior is crucial for predicting potential failures and ensuring the safety of downstream areas. For instance, the Karkheh Earth Dam exhibited maximum settlement differences of 0.05 m and 0.01 m during construction and operation stages, respectively, as monitored using Mohr-Coulomb and Hardening Soil models. Similarly, significant settlements ranging from 0 to 832 mm were recorded at the Tilong Dam, particularly at mid-sections, highlighting the necessity for accurate predictive models to assess structural health.

In terms of predictive modeling, a machine learning model developed for Concrete Face Rockfill Dams enhanced predictive accuracy and safety assessments by analyzing multiple factors affecting settlement (Shao et al., 2023). Furthermore, a multi-input Long Short-Term Memory (LSTM) network was proposed to improve settlement predictions by accounting for random errors and environmental parameters, which is crucial for long-term safety evaluations (Qi et al., 2023).

2.9 GeoStudio 2018 Software

GeoStudio is composed of eight software products that enable everything from simple to complex analyses. When integrated, the products offer a broader analytical environment that offers significantly more power and capabilities. The fully integrated software suite includes limit equilibrium stability analysis and seven finite element applications for modeling geotechnical and earth science problems. The suite includes: SLOPE/W (Slope stability analysis), SEEP/W (Groundwater seepage analysis), SIGMA/W (Stress-deformation analysis), QUAKE/W (Dynamic earthquake analysis), TEMP/W (Thermal analysis), CTRAN/W (Contaminant transport analysis), and VADOSE/W (Vadose zone and soil cover analysis), and AIR/W (Airflow analysis).

2.9.1 SEEP/W Model

SEEP/W is a finite element software product that is part of the GEO-SLOPE International suite, a leader in geotechnical modeling software. It aids in analyzing groundwater seepage and excess pore-water pressure problems within porous materials such as soil and rock. The model's comprehensive formulation allows analyses ranging from simple, saturated steady-state problems to sophisticated, saturated-unsaturated, time-dependent problems.

SEEP/W allows engineers to analyze and design for geotechnical and civil problems. The unique CAD-like technology in SEEP/W allows users to generate a finite element mesh by drawing regions on the screen, interactively applying boundary conditions, specifying material properties, and estimating material property functions from easily measured parameters like grain size, saturated conductivity, and saturated water content.

Once the seepage problem is solved, SEEP/W offers many tools for viewing results. Users can generate contours or x-y plots of any computed parameter, such as head, pressure, gradient, velocity, and conductivity. Velocity vectors show flow direction and rate. Users can interactively query computed values by clicking on any node or flux section, then export results into other applications, such as Microsoft Excel or Word, for further analysis or to prepare presentations. Using SEEP/W to analyze the expected quantity of seepage through the embankment and dam foundation requires sets of parameters such as the model section of the dam, permeability coefficient of material, piezometer readings, and boundary conditions.

2.9.2 SLOPE/W Model

SLOPE/W is the leading software product for analyzing the stability of earth and rock slopes. SLOPE/W can effectively analyze both simple and complex problems for a variety of failure modes, pore-water pressure conditions, soil properties, loading conditions, and reinforcement options.

SLOPE/W can accommodate pseudo-static analysis, limit state design, probabilistic and sensitivity analysis, and rapid drawdown analysis. It can be combined with SIGMA/W for stress-based stability analysis or QUAKE/W for Newark deformation. Full integration with other GeoStudio finite element products allows the stability of slopes and excavations to be analyzed through time.

2.9.3 SIGMA/W Model

SIGMA/W can be used to perform stress and deformation analyses of earth structures. Its comprehensive formulation makes it possible to analyze both simple and highly complex problems. SIGMA/W can perform a simple linear elastic deformation analysis or a highly sophisticated, nonlinear elastic-plastic effective stress analysis.

The many constitutive soil models allow the user to represent a wide range of soils or structural materials. In addition, SIGMA/W can model pore-water pressure generation and dissipation in a soil structure in response to external loading.

2.10 Concluding Remark

For the Bohol Qawlo CFRD, founded on a permeable foundation in Somaliland, conducting an integrated seepage, stability, and deformation analysis using GeoStudio 2018 is essential to comprehensively assess its integrity and safeguard against critical risks. This coupled numerical approach will quantify seepage forces and exit gradients to evaluate piping potential through the foundation, utilize resulting pore pressures for precise slope stability calculations under all operational scenarios, and estimate foundation settlement to ensure long-term serviceability. The findings from this analysis are crucial for validating the design, informing any necessary mitigation measures, and ultimately ensuring the dam's safe performance and sustainability as a vital water resource for the region.

CHAPTER THREE: MATERIAL AND METHODS

3.1 Description of the Study Area

The Bohol Qawlo Dam is situated within the Bohol Qawlo sub-basin of the larger Durdur Basin. Located at coordinates 9.43° N and 43.40° E, the dam is under the jurisdiction of Gabiley City, which lies 5 km away on the Haud Plateau at an elevation of 1,467 meters. The dam manages a watershed area of 320 km² (120 sq. miles). Construction was completed in 2020, and the facility became fully operational in 2021.

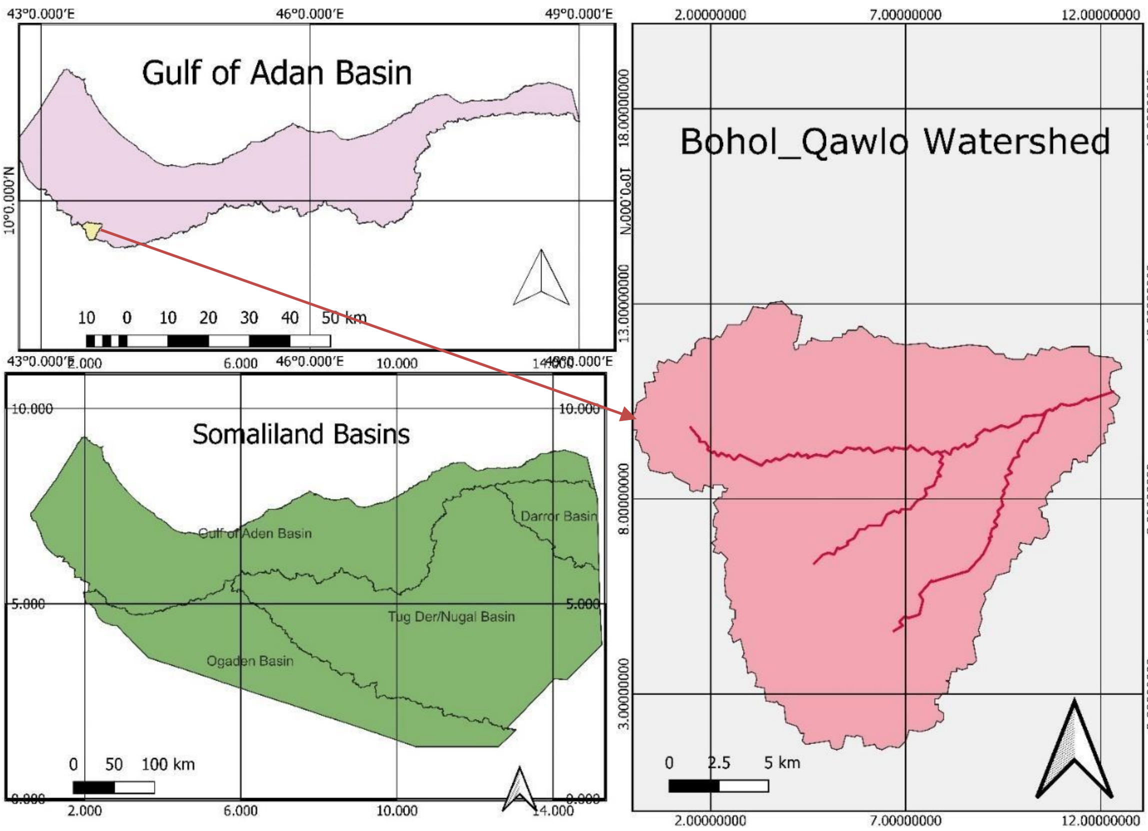


FIGURE 1: dam catchment area

Table 1: Specification of the Bohol Qawlo dam body (source MECCO)

No	Type	Classification
1	Type of the dam	Concrete Faced Rock fill dam
2	Fill material	Reinforced concrete cement , Masonry Roc , Rock fill Material
3	Dam height (m)	16m
4	Dam crest level (m)	18m
5	Crest length (m)	200m
6	Active Height	13m
8	Minimum Elevation	1387m
9	Maximum Elevation	1402.5 m
10	Spillway Crest Elevation	1400.241 m
11	Free Board	3m
12	Full Supply Level (FSL)	1400.5 m
13	Capacity at FSL (1400.5 m)	1,015,794.89 m^3
14	Capacity at 1400 m	900,244.89 m^3
15	Water Fetch Length (@ FSL)	0.70km
16	Embankment slope	1.5H:1V

3.2. Geology at the dam location

The dam is situated where a stream passes between two small mountainous formations. Geologically, these outcrops belong to the Tertiary period. According to the World Geological Map, the area likely contains a mix of hard volcanic rocks (e.g., basalt) and softer sedimentary rocks (e.g., sandstone and limestone). The geological features presented in the following figures were documented during the on-site dam assessment.

Figure 3 Geological rocks at the site area

Figure 4 Downstream of the dam

Figure 2 Reservoir of dam

3.3 The Rainfall of the Catchment

Annual rainfall for the catchment area was based on historical data from the Gabiley meteorological station for the period 2004–2025. The data showed a long-term average of

504 mm.

Despite this relatively healthy average for a semi-arid region, the rainfall pattern exhibited significant year-to-year variability. The data indicated annual totals ranging from 340 mm in severe drought years to 780 mm in extremely wet years. This fluctuation underscored the critical importance of water management infrastructure in ensuring a stable water supply for both the community and agricultural activities.

3.4 Materials Used

To achieve the study objectives, both GeoStudio software and analytical methods were employed. GeoStudio 2018 R2 was used to assess the performance of the dam, incorporating both the Limit Equilibrium Method and the Finite Element Method. Specifically:

- SEEP/W 2018 was applied to estimate seepage through the dam body and foundation.
- SLOPE/W 2018 was used for slope stability analysis.
- SIGMA/W was used for stress and deformation analysis.
- In addition, QGIS was utilized to delineate the dam's watershed using Digital Elevation Model (DEM) data, relative to the existing performance of the dam.

3.5. Data Collection

Before conducting any study, it is fundamental to thoroughly search for relevant data. Accordingly, the key tasks involved gathering the necessary information about the study area. This study required two types of data collection methods, obtained using different techniques. The primary data were collected through direct engagement with the construction company responsible for the dam. This was done to verify whether there were any differences in the dam’s geometry, as well as to assess its stability, seepage conditions, and the overall geology of the site.

3.5.1 Secondary data collection

The Secondary data for this research was obtained through direct consultation with the MECCO Construction Company, which provided the original design specifications and construction records. To ensure the accuracy of this data, a comprehensive field investigation was conducted at the Bohol Qawlo dam site. The purpose of this site visit was to verify the as-built geometry of the embankment and identify any discrepancies between the design drawings and the actual structure. Additionally, the visit allowed for an on-site assessment of the local geological conditions and a visual inspection of the dam's current stability and seepage performance

TABLE 2 : Geotechnical properties of the material (from MECCO)

Material Type	γ_{un-sat} (kN/m³)	γ_{sat} (kN/m³)	Kx (m/s)	Ky (m/s)	E (MPa)	nu	C (kN/m²)	phi (°)	psi (°)
Colluvium soil	18	20	6.37e-06	6.37e-07	38	0.35	6	32	2
Rock-fill	20	22	5.03e-02	5.03e-02	150	0.25	0	42	8
Reinforced Concrete Cement	24	24	1.16e-12	1.16e-10	25,000	0.2	2500	45	0
Masonry rock	22	23	1.16e-08	1.16e-09	3500	0.2	500	40	0

3.6. Data analysis

In this thesis study utilized for analyzing the seepage and slope stability is numerically by GeoStudio computer program (SEEP/W and SLOPE/W) and analytical methods. The study is based on visual observation and accessible data display at the design document.

3.6.1 Analyzing Seepage of Bohol-qawlo dam by using SEEP/W

To achieve the overall seep water through the dam by numerical method (SEEP/W) were utilized by using primary and secondary data. The SEEP/W software is a sub program of the Geo-Slope software which is utilized to accommodate leakage problems through porous soil media.

3.6.2 Safety Criteria

Safety evaluation of embankment dams should satisfy the recommended criterion by safety regulations or codes issued by authorized agencies. Among the numerous dam safety regulation, both (USACE, 2003) Table 1: Various Load Cases and Minimum Required Factor of Safety.

Table 3 Minimum Required Factor of Safety (USACE, 2003)

Case	Loading Condition	Critical Slope	FoS
I	End of construction	Upstream	**1.3**
		Downstream	**1.3**
III	Steady state seepage	Upstream	**1.5**
		Downstream	**1.5**
IV	Steady state seepage with earthquake	Upstream	**1.1**
		Downstream	**1.1**

3.6.3 Slope Stability Analysis using SLOPE/W

The evaluation of the stability of Bohol-Qawlo Embankment Dam analyzed using the limit equilibrium method of SLOPE/W software. The analytical method for evaluating the static stability of an embankment method had been utilized by using dam cross section and soil test data. Accordingly, the stability analyses had been carried out in order to determine the factor of safety. The stability analysis methods used in SLOPE/W are Bishop, Spencer, Morgenstern Price and ordinary (GEO-SLOPE International Ltd., 2010b). Stability of the upstream and downstream slopes of the embankment is analyzed for the most critical loading conditions that may occurred during the life of the dam, these loading conditions typically include

3.6.4 End of construction condition

Computation of stability at the end of construction for both upstream and downstream slopes was performed using drained strengths in free-draining materials. For materials that drain slowly and Total stress analysis with Un-drained strengths and zero pore water pressure Factor of safety against sliding.

$$F = \frac{Mr}{Md} = \frac{\mathrm{CLtan}\varnothing\ (N - U)}{ST}$$

3.6.5 Steady state seepage condition

The stability analysis for both upstream and downstream slopes under steady state condition has been checked by considering NWL for normal loading condition. The phreatic surface computed with the help of Seep/W was used to setup the pore water pressure line in the stability analysis. Critical condition for d/s slope occurs when the reservoir is full and percolation is at its maximum rate.

$$F.S = \frac{CL + \tan\text{Ø}\,(N - U)}{ST}$$

3.6.6 Analysis methods for the slope stability

Limit equilibrium analysis is carried out using the Slope/W software for the slope stability of the dam. The analysis type is then selected and it is determined that failure has follow a right to left path. The Morgenstern Price analysis and half-sine function was selected but the software also gives the result of factor of safety for, Bishop, Morgenstern-Price and Spencer's method analysis type.

3.6.7 Morgenstern-Price method

This method considers not only the normal and tangential equilibrium but also the moment equilibrium for each slice in circular and non-circular slip surfaces. The equations are written for a slice of infinitesimal thickness as: The factor of safety with respect to force equilibrium is:

$$F_f = \frac{\sum(c'l + (p - ul)\tan\phi')\cos\alpha}{\sum p \sin\alpha}$$

And, the factor of safety with respect to moment equilibrium is:

$$F_m = \frac{cl + (p - ul)\tan\phi'}{W \sin\alpha}$$

3.6.8 Spencer's method

According to this method, considering overall force equilibrium and overall moment, two values of factor of safety Ff and FM are obtained. This is because a total of 2n-1 assumptions have been made and the problem is over specified. The factor of safety be derived based on the overall moment equilibrium about a common point (O):

$$F_f = \frac{\sum c'l + (p - ul)\tan\phi'}{\sum W \sin\alpha}$$

The factor of safety (Ff) can be derived based on the overall force equilibrium as:

$$F_f = \frac{\sum c'l + (p - ul)\tan\phi'}{\sum(W - (X_R - X_L))\tan\alpha}$$

$$FS = \frac{1}{\sum W \sin\alpha} \sum \left[c\beta + W \tan\phi - \frac{c\beta}{FS} \sin\alpha \tan\phi \right]$$

3.6.9 SIGMA/W Model

SIGMA/W can be used to perform stress and deformation analyses of earth structures. Its Comprehensive formulation makes it possible to analyze both simple and highly complex Problems. SIGMA/W can perform a simple linear elastic deformation analysis or a highly sophisticated, nonlinear elastic-plastic effective stress analysis. The many constitutive soil models allow you to represent a wide range of soils or structural materials. In addition, SIGMA/W can model the pore-water pressure generation and dissipation in a soil structure in response to external loading.

3.7 Framework of the Study

The methodology flowchart of the Bohol Qawlo CFRD is presented as follows.

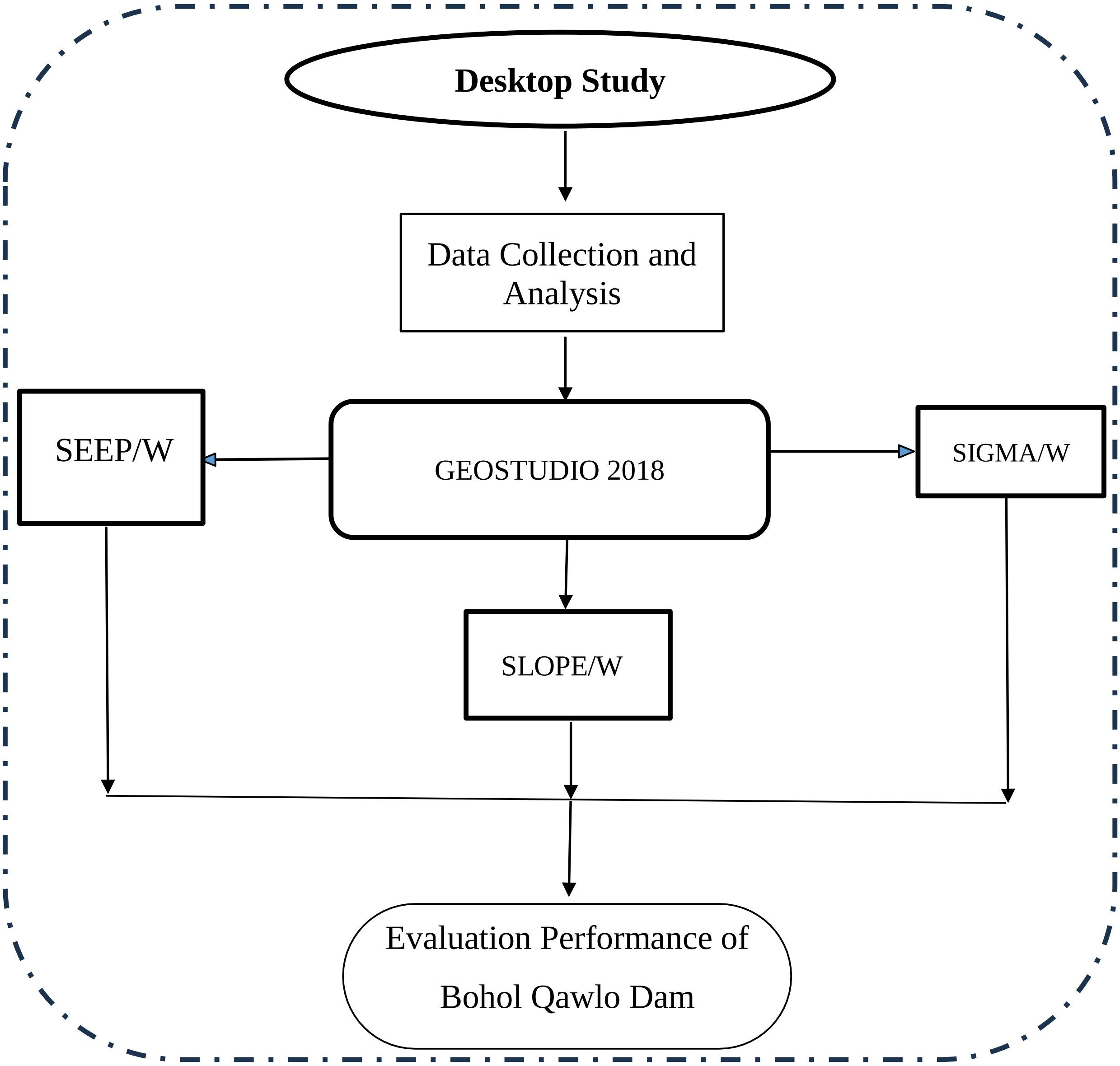


FIGURE 5 : Framework of the thesis Methodology

CHAPTER FOUR: RESULTS AND DISCCUSION

4.1 Results Seepage Analysis

The steady-state seepage analysis was conducted to determine the position of the phreatic line, pore water pressure distribution, and hydraulic gradients within the dam embankment and its foundation. The analysis assumed the reservoir was at the Full Supply Level (FSL).

The total head distribution analysis revealed that the phreatic line, indicated by the blue dashed line, was successfully established at the interface between the dam body and the foundation, without penetrating the rock fill embankment. This result confirmed that the upstream concrete face functioned effectively as an impermeable barrier, keeping the embankment material unsaturated and preserving its shear strength. Furthermore, the gradual drop in total head contours from upstream to downstream indicated a controlled dissipation of energy through the foundation rather than the dam body.

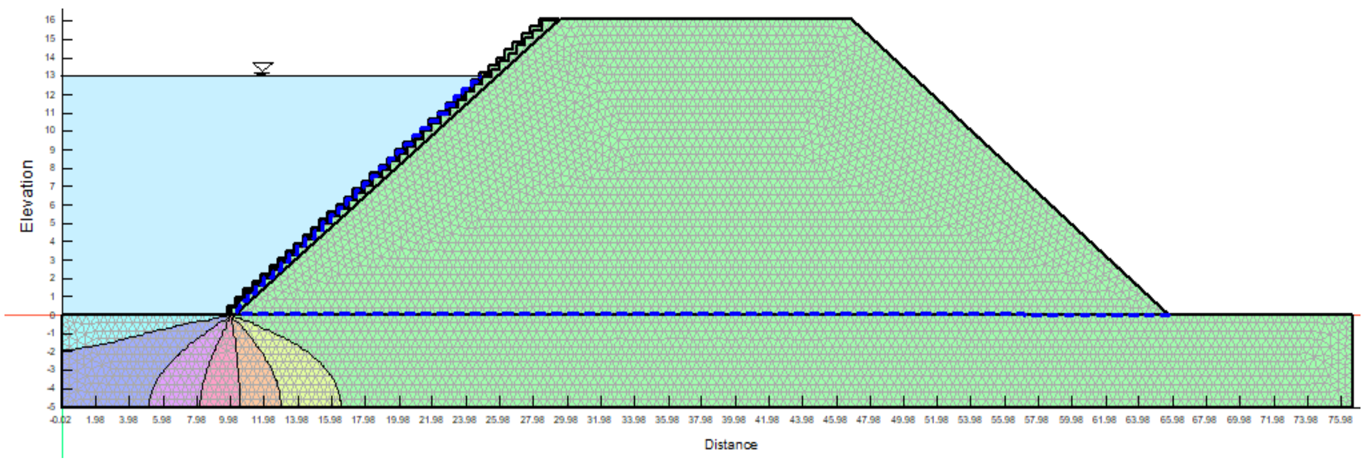


FIGURE 6 : Total head distribution and location of phreatic line.

The SEEP/W analysis for the Concrete Face Rockfill Dam (CFRD) revealed seepage behavior characteristic of highly permeable embankment systems, where the Water X-Flux (horizontal flow) was almost entirely restricted to the saturated zone at the foundation interface. The results indicated that the phreatic surface dropped steeply through the rockfill body, creating a concentrated flow layer at the base with peak flux rates exceeding 2.4×10^{-4} m³/sec/m².

This behavior was strongly validated by the case study of the Dhap Dam in Nepal, the country's first Concrete Faced Rockfill Dam (CFRD). Research by (Anup Lamichhane, 2021) on the Dhap Dam confirmed that in CFRD structures, the rockfill body typically remained dry and stable, while the critical seepage path shifted to the foundation layers, particularly when constructed on permeable Sandy colluvium .

4.1.2 Technical Analysis

To quantitatively assess the safety of the embankment dam against piping and internal erosion, the simulation results were evaluated against the safety criteria outlined in USACE EM 1110-2-1901 (Seepage Analysis and Control for Dams) and USBR design standards. The assessment involves determining the critical hydraulic gradient (i_{cr}) of the foundation soil and comparing it to the actual exit gradients calculated by the SEEP/W model.

4.1.3 Determination of Critical and Allowable Gradients

The critical hydraulic gradient (i_{cr}) represents the threshold at which the upward drag force of seepage water equals the submerged weight of the soil particles, leading to a "quick" condition or boiling. For the Sandy Loam foundation, this was calculated using the specific gravity (Gs) and void ratio (e) of the soil:

Critical hydraulic gradient (icr) for Heave/Piping:

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

Based on the material properties defined in the model, the critical gradient was determined to be:

$$i_{cr} = 0.94$$

To ensure a safe design, a standard Factor of Safety (FS) is applied. According to USACE guidelines, a safety factor of 4.0 is recommended for exit gradients at the toe of the dam to prevent piping. The maximum allowable exit gradient (i_{allow}) is therefore calculated as:

$$i_{allow} = \frac{\text{icr}}{FS} = \frac{0.94}{4} = 0.235$$

Consequently, any calculated exit gradient exceeding 0.235 would be considered unsafe.

The steady-state seepage analysis performed yielded the following results:

Table 4 Summary of analysis results (USACE EM 1110-2-1901)

Parameter	Allowable Value	Calculated Value	Assessment & Implication
Hydraulic Gradient,	0.16 - 0.24 (Safe Operating)	37.7 - 376.8 (Actual at Interface)	Catastrophic Excess. The actual seepage force is 150 to 2,350 times the safe limit.
Factor of Safety vs. Piping	4.0 - 6.0 (Required Minimum)	0.025 - 0.0025 (In-Use)	Total Non-Compliance. The system is operating at < 1% of the required safety margin. Failure is imminent.
Seepage Velocity	~ 1×10−5m/s (Erosion Threshold)	~ 6.9×10−4m/s	~70x higher than the velocity known to initiate particle transport in fine soils.

In summary, the permeability range clearly shows the system is failing. Immediate intervention is essential.

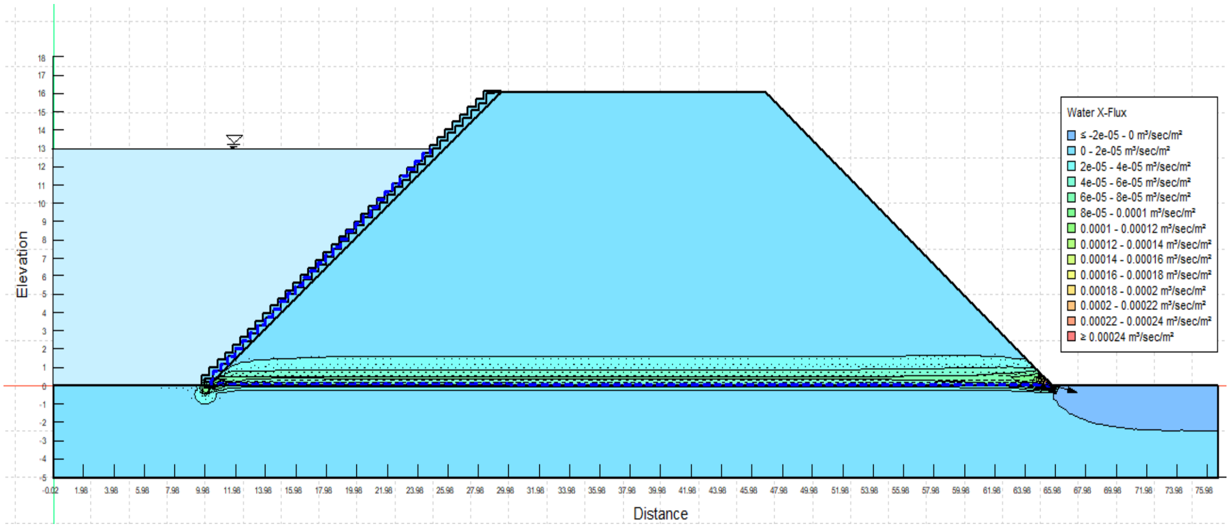


FIGURE 7 : seepage water x- flux

The Water Pressure Head graph (Figure 9) confirmed the design performance of the Concrete Faced Rockfill Dam. The simulation showed that positive water pressures (pink/purple zones) were confined strictly to the foundation and reservoir, while the rockfill embankment exhibited negative pressure heads (green zones), indicating it remained fully unsaturated and stable.

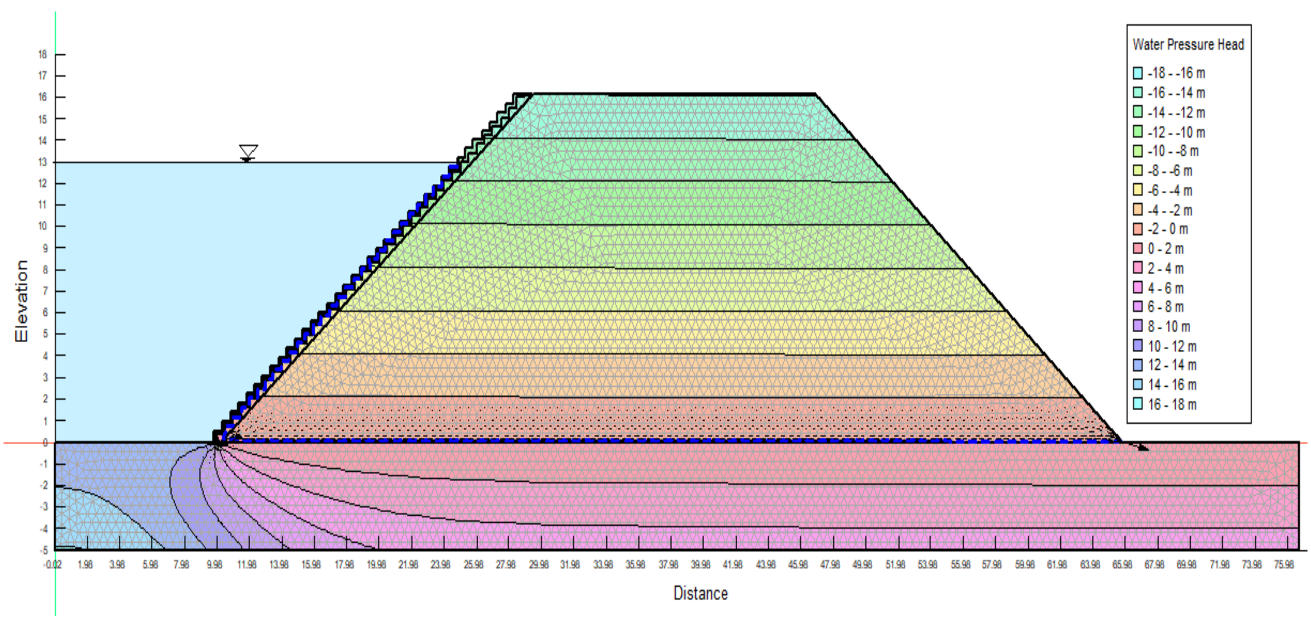


FIGURE 8 Water Pressure head

Figure 10 presented the contours of the horizontal hydraulic gradient (Water X-Gradient). The results highlighted the functional efficiency of the concrete face. A steep hydraulic gradient was observed exclusively along the upstream face elements, indicated by the dark blue contours (values ranging from -70 to -20). This concentration of gradient confirmed that the total hydraulic head loss occurred almost entirely across the concrete face, validating its role as the sole impermeable barrier. Conversely, the rockfill embankment and the majority of the foundation exhibited near-zero gradients (indicated by the light blue zone, 0 to 5). This confirmed that there was no significant horizontal seepage flow through the dam body, ensuring the stability of the downstream rockfill.

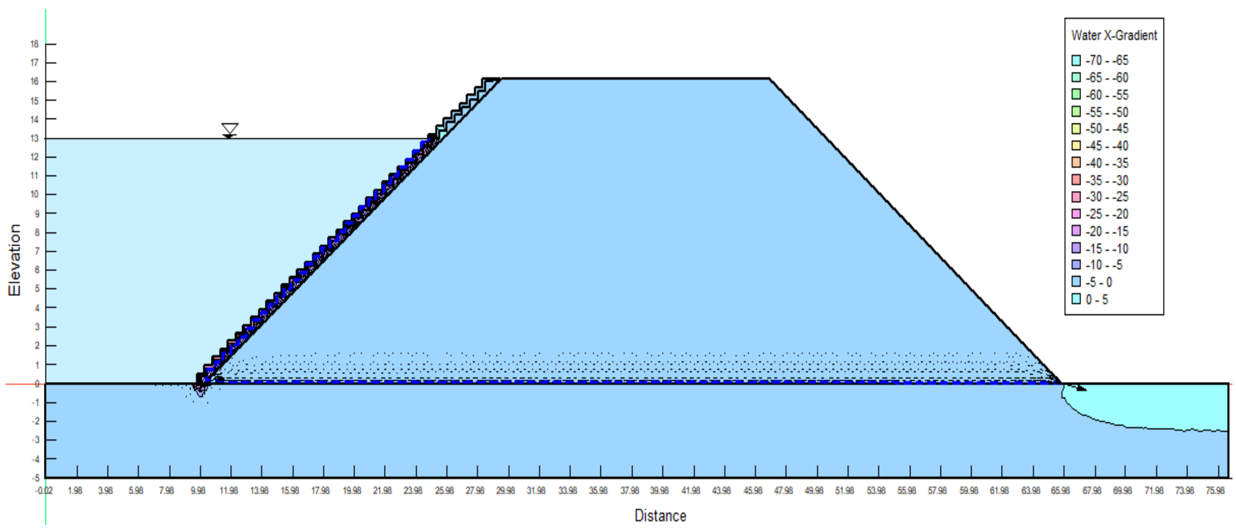


FIGURE 9 Water X-Gradient

Figure 11 depicted the vertical hydraulic gradient distribution. The analysis further corroborated the effectiveness of the impervious facing. Significant vertical gradients were observed only along the concrete face interface (indicated by dark blue contours, values < -10), representing the sharp dissipation of reservoir head. The main rockfill embankment and the foundation exhibited low vertical gradients (yellow and orange zones, values between -5 and 5). Notably, the low gradient values at the downstream toe indicated the absence of significant uplift pressures or upward seepage forces.

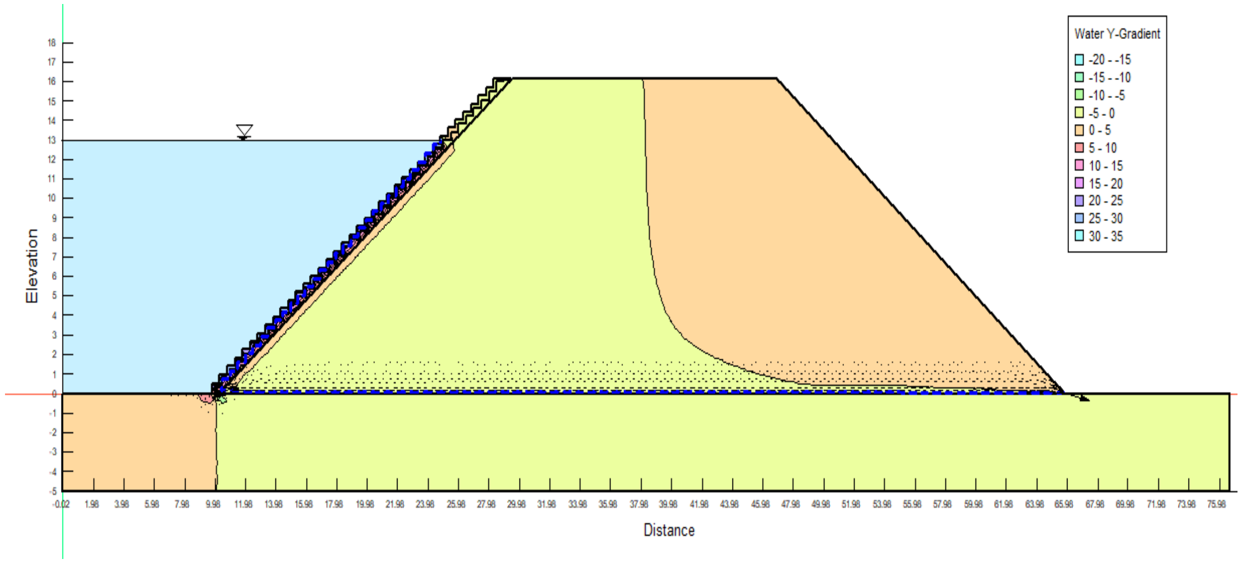


FIGURE 10 Water Y-Gradient

Figure 12 illustrated the distribution of pore water pressure (in kPa), quantifying the hydraulic stress state within the materials. The foundation exhibited positive pore water pressures that increased with depth (shown by yellow to red contours), peaking at approximately 160 kPa; this confirmed the expected full saturation and hydrostatic behavior in the foundation zone.

In contrast, the rockfill embankment maintained negative pore water pressures (suction) throughout, ranging from 0 kPa at the base to -160 kPa at the crest (green to blue contours). These negative values demonstrated that the rockfill material remained unsaturated, highlighting the effectiveness of the upstream concrete face. The sharp pressure discontinuity observed at the upstream slope verified that the facing successfully blocked reservoir water from pressurizing the embankment fill.

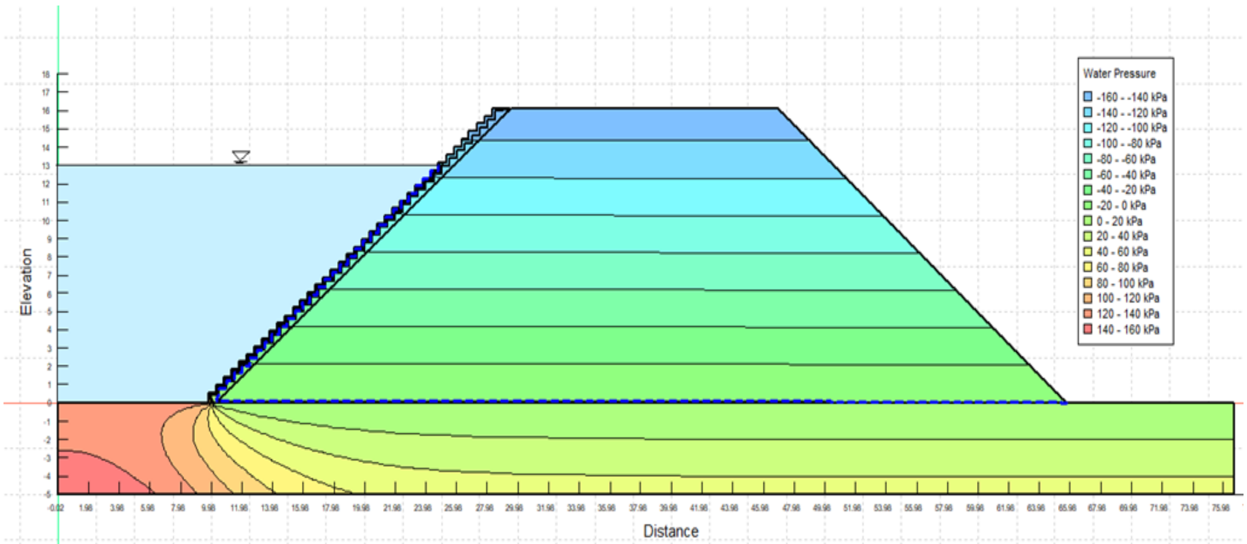


FIGURE 11 Water Pressure

Figure 13 presented the degree of saturation contours, clearly distinguishing the saturated phreatic zone from the unsaturated embankment. The foundation region displayed pink contours (S ≥ 0.95), indicating full saturation consistent with the groundwater table. In contrast, the rockfill body maintained low saturation values between 0.30 and 0.45 (cyan and teal zones). The absence of high-saturation zones within the embankment confirmed that the upstream face functioned correctly, preventing water ingress and preserving the shear strength of the rockfill material.

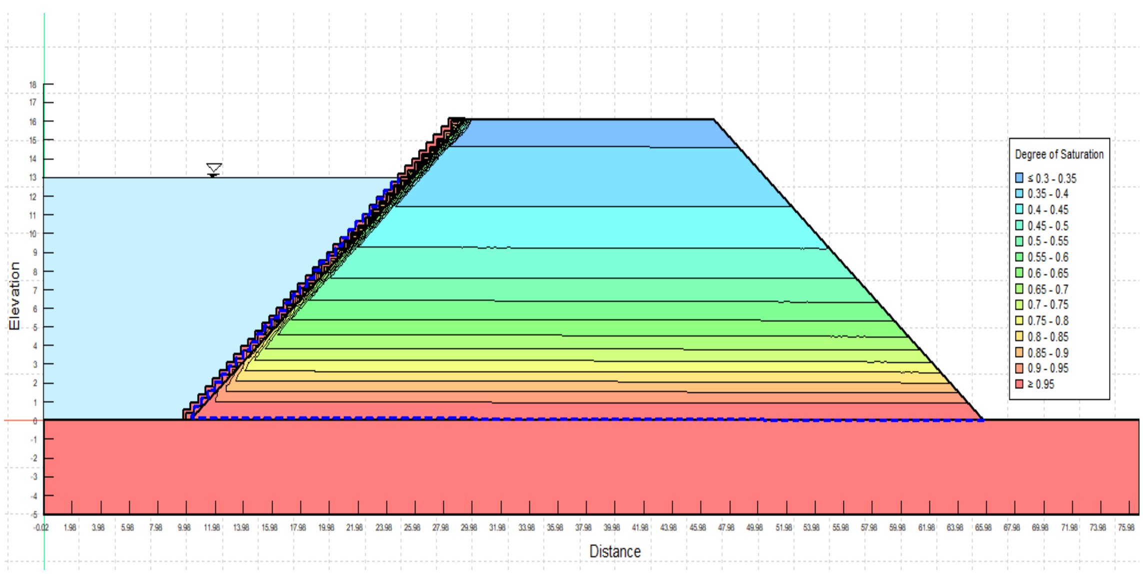


FIGURE 12 : Degree of Saturation

Figure 14 illustrated the hydraulic conductivity functions assigned to the materials in the model. The 'Rockfill Material' (blue curve) exhibited a high saturated hydraulic conductivity of approximately 5×10^{-2} m/s, characterizing it as a free-draining material; the curve also demonstrated a reduction in conductivity as matric suction increased. Crucially, the 'RCC' material (representing the concrete face) was defined with a constant, extremely low conductivity of 1×10^{-11} m/s. This input parameter dictated the impermeable behavior observed in the pressure and gradient results, successfully simulating the watertight nature of the concrete facing.

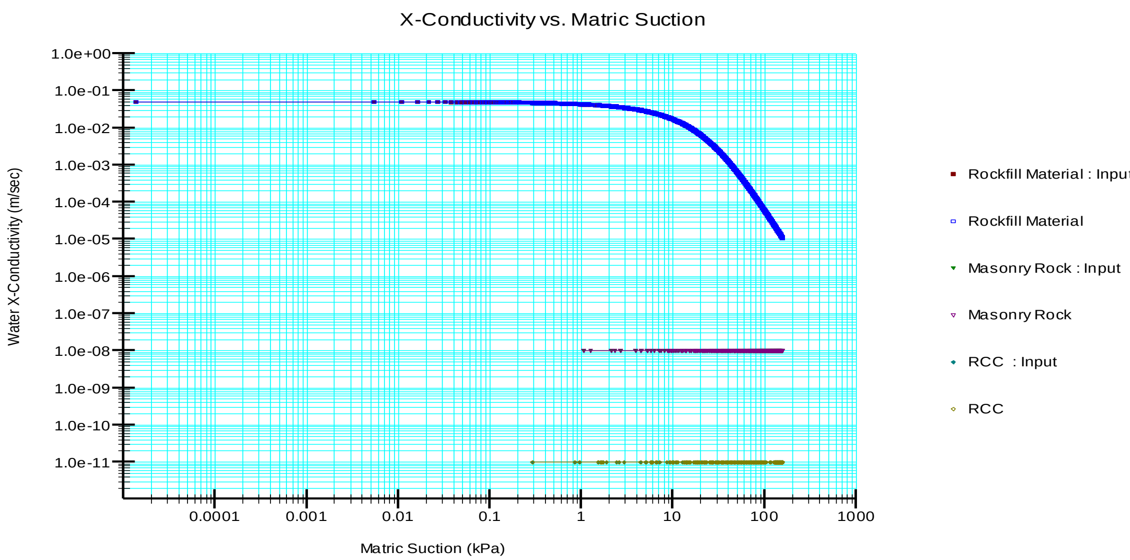


FIGURE 13 : X - Conductivity vs. Matric Suction

4.3 Result of Slope Stability Analysis

Following the seepage analysis, it was essential to assess the stability of the dam slopes. This evaluation was conducted using SLOPE/W software to analyze both the upstream and downstream surfaces under standard loading conditions, utilizing multiple limit equilibrium methods (Bishop, Morgenstern-Price, and Spencer).

The initial assessment focused on the embankment dam under the "End of Construction" loading condition. Figure 15 presented the results for the upstream face at this stage, identifying the critical slip surface. The calculated minimum Factor of Safety (FOS) was 2.279, as marked in red. This value significantly exceeded the standard recommended minimum of 1.3 for the end-of-construction phase.

The critical failure surface (highlighted in green) was shallow and confined within the upstream rockfill shell; this indicated that the shear strength of the compacted rockfill was sufficient to maintain stability. This high factor of safety confirmed that the upstream slope provided a rigid support system for the concrete face, thereby minimizing the risk of deformation-induced damage to the impermeable slab.

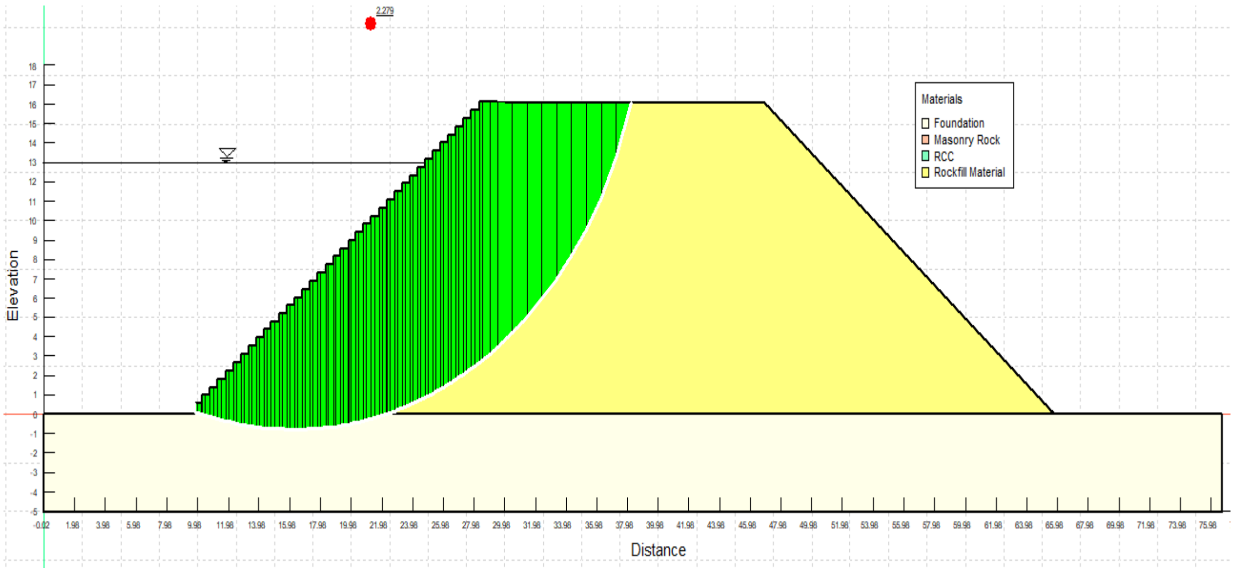


FIGURE 14 FOS for Upstream at the end of construction

Figure 16 displayed the slope stability analysis results for the downstream slope at the end of construction. The calculated minimum Factor of Safety (FOS) was 1.490; this value satisfied the standard safety criteria (which typically require FOS > 1.3 for this loading condition), thereby confirming the stability of the downstream embankment design.

The critical slip surface (shown in green) was contained within the rockfill shell and exited at the downstream toe. This analysis demonstrated that the compacted rockfill possessed sufficient shear strength to resist gravitational driving forces, ensuring the structural integrity of the dam's downstream face prior to reservoir impoundment.

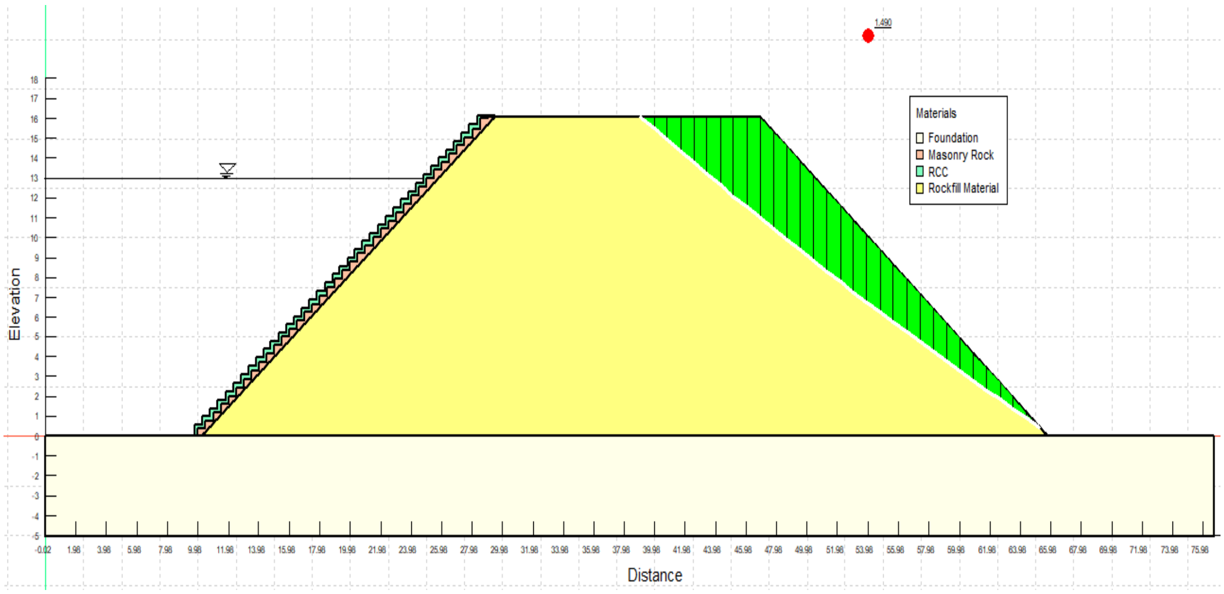


FIGURE 15 FOS for Downstream at the end of construction

Table 4 summarized the Factors of Safety (FOS) calculated for the upstream (U/S) and downstream (D/S) slopes using the Morgenstern-Price and Spencer methods. These results were evaluated against USACE (2003) guidelines, which mandate a minimum FOS of 1.3 for the End of Construction case.

The analysis yielded an FOS of approximately 2.27 for the upstream slope and 1.49 for the downstream slope (using the Spencer method). Since both values exceeded the regulatory threshold of 1.3, the dam embankment was deemed stable and safe under the End of Construction loading condition.

Table *4* End Construction Case *(USACE, 2003)*

Loading Condition	**End Construction Case**			**State**
Method of analysis at	**Morgenstern price**	**Spencer**	**Bishop**	
FOS at Critical analysis				
U/S	2.279	2.270		OK
D/S	2.279	1.490		OK
Minimum Required Factor of Safety	1.3	1.3		

4.2.2 Slope stability long term slope stability

Figure 17 illustrated the slope stability analysis for the upstream face under long-term steady-state seepage conditions (Full Reservoir). The calculated Factor of Safety (FOS) was 4.714, representing a significant increase compared to the End of Construction stage (FOS = 2.279). This substantial rise was characteristic of Concrete Faced Rockfill Dams (CFRD).

The analysis showed that under full reservoir conditions, the hydrostatic water pressure acted perpendicular to the upstream concrete face. This hydraulic load served as a stabilizing force, increasing the normal stress on the rockfill elements and effectively 'clamping' the upstream slope in place. Consequently, the reservoir water functioned as a buttress, resulting in an exceptionally high factor of safety against upstream sliding during normal operation.

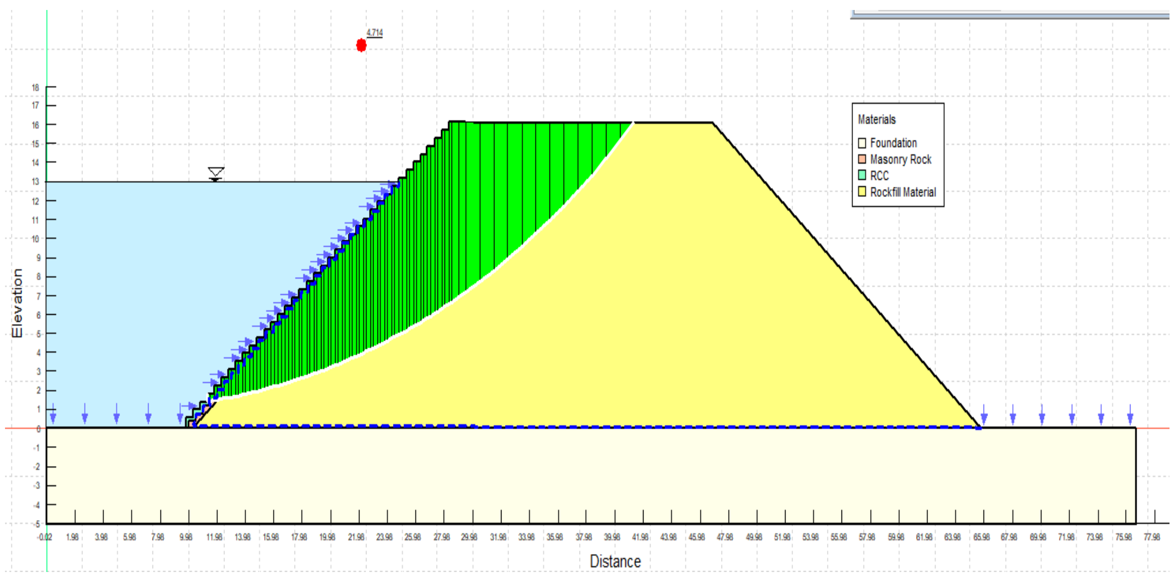


FIGURE 16 Upstream at long term stability

Figure 18 presented the slope stability analysis for the downstream embankment under long-term steady-state seepage conditions. The calculated Factor of Safety (FOS) was 1.731, as indicated by the red marker; this value exceeded the standard safety requirement of 1.5 for steady-state loading conditions.

When comparing this result to the End of Construction case (FOS = 1.490), the stability of the downstream slope showed clear improvement. This behavior highlighted the effectiveness of the concrete face design: because the downstream rockfill shell remained fully unsaturated (dry) during reservoir operation, no destabilizing pore water pressures developed within the slope.

The critical slip surface remained confined to the dry rockfill material, ensuring robust long-term stability.

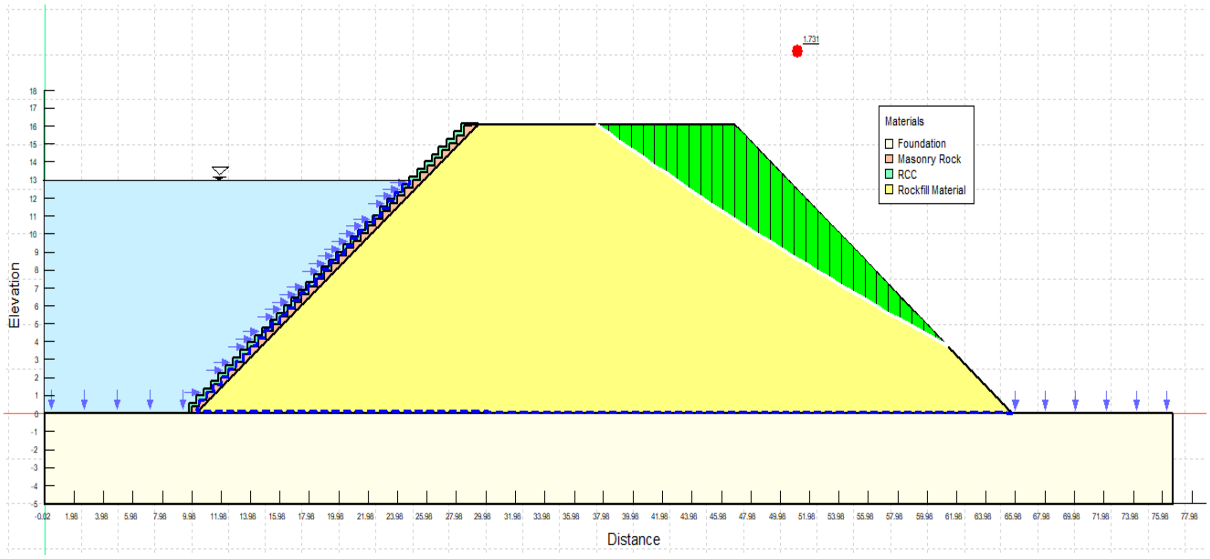


FIGURE 17 Downstream at long term stability

Figure 19 illustrated the spatial distribution of water pressure head within the dam-foundation system, with contours effectively delineating the saturated and unsaturated zones. The foundation exhibited positive pressure heads (yellow and orange zones, 0 to 18 m), confirming a fully saturated condition consistent with steady-state seepage under the dam.

In contrast, the rockfill embankment was characterized entirely by negative pressure heads (green and cyan zones, -18 to 0 m). These negative values indicated that the pore water pressure was below atmospheric pressure (suction), proving that the embankment material remained unsaturated. The sharp boundary at the foundation interface demonstrated that the phreatic surface was successfully confined to the foundation level, preventing saturation of the downstream shell.

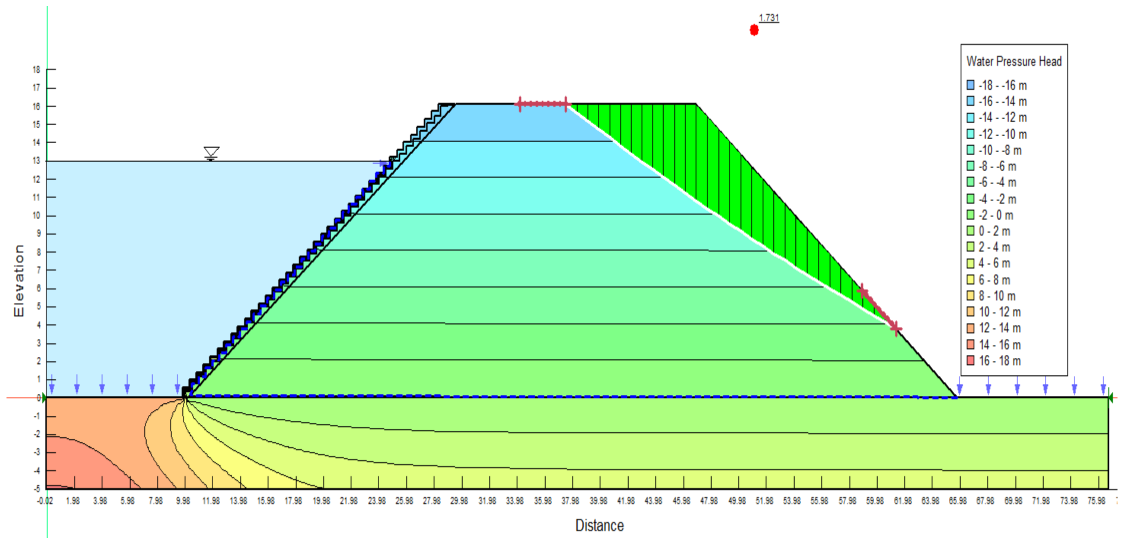


Figure 18 Water Pressure Head

Figure 20 maps the pore water pressure in kilopascals (kPa). The analysis clearly distinguishes between the saturated foundation (positive pressures up to 160 kPa, shown in red/yellow) and the unsaturated rockfill embankment (negative pressures/suction down to -80 kPa, shown in green). This confirms that positive hydrostatic pressures are successfully confined to the foundation layer, keeping the embankment material in a dry, stable state.

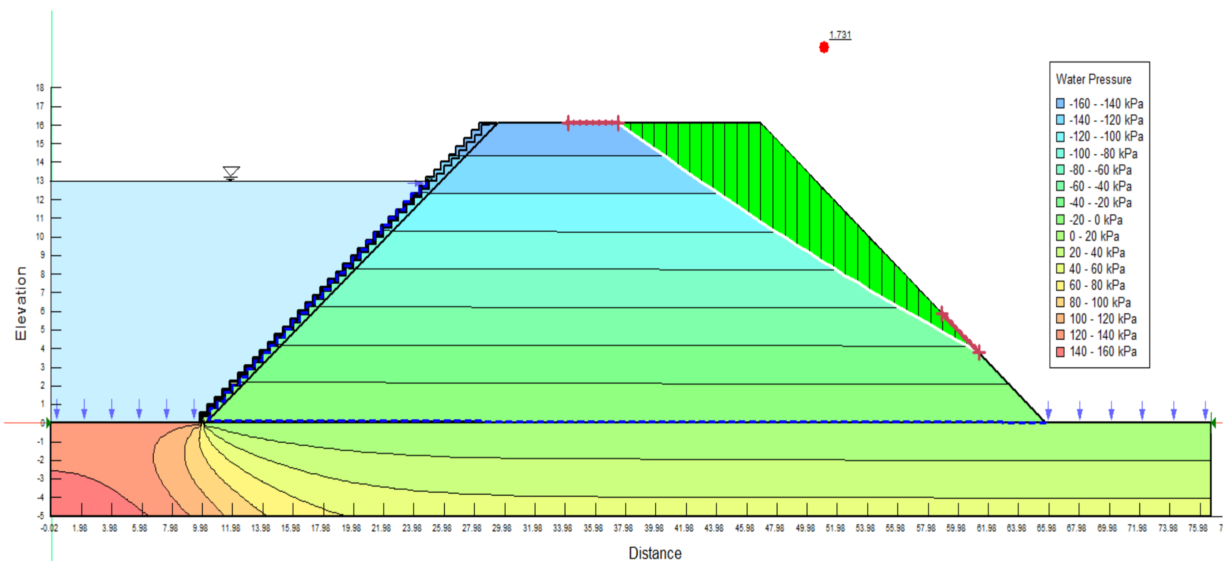


FIGURE 19 Pore water pressure distribution

Table 5 summarized the results of the slope stability analysis under the long-term steady state loading condition. The analysis evaluated the Factor of Safety (FOS) for both the upstream (U/S) and downstream (D/S) slopes using three limit equilibrium methods: Morgenstern-Price, Spencer, and Bishop.

The results indicated that the embankment dam met the required safety standards. For the upstream slope, the calculated FOS values ranged from 4.614 (Morgenstern-Price) to 4.714 (Bishop), demonstrating high stability. For the downstream slope, all three methods yielded a consistent FOS of 1.731, indicating uniform results across the different analysis techniques.

All calculated FOS values exceeded the minimum required Factor of Safety of 1.5 as established by the USACE (2003) guidelines. Consequently, the stability of both the upstream and downstream slopes was confirmed under long-term steady state conditions.

Table 5 Slope Stability Long Term Steady State

Loading Condition	**Slope Stability Long Term Steady State**			**Status**
Factor of Safety at Critical Conditions	Morgenstern price	Spencer	Bishop	
U/S	4.614	4.624	4.714	Ok
D/S	1.731	1.731	1.731	OK
Minimum Required Factor of Safety USACE, 2003	1.5	1.5	1.5	

4.2.3 Analysis of Slope Stability under Seismic Conditions

To evaluate the structural integrity of the embankment under earthquake conditions, a seismic stability analysis was conducted using the pseudo-static method. This well-established approach simplifies the complex, dynamic shaking of an earthquake into a constant, unidirectional inertial force applied to the potential sliding mass. The primary objective was to determine the Factor of Safety (FOS) against slope failure during a design-level earthquake, ensuring the dam satisfies safety standards.

The horizontal inertial force (Fh) is calculated as the product of the horizontal seismic coefficient (Kh) and the weight of the sliding mass (W), expressed as:

$$\mathrm{Fh} = Kh \times W$$

The seismic coefficient (Kh) was derived based on the Peak Ground Acceleration (PGA) of the site. Using the World Earthquake Model, the site PGA was determined to be 0.025g. Following standard engineering practice (typically recommended by USACE guidelines), the seismic coefficient was selected as 50% of the PGA:

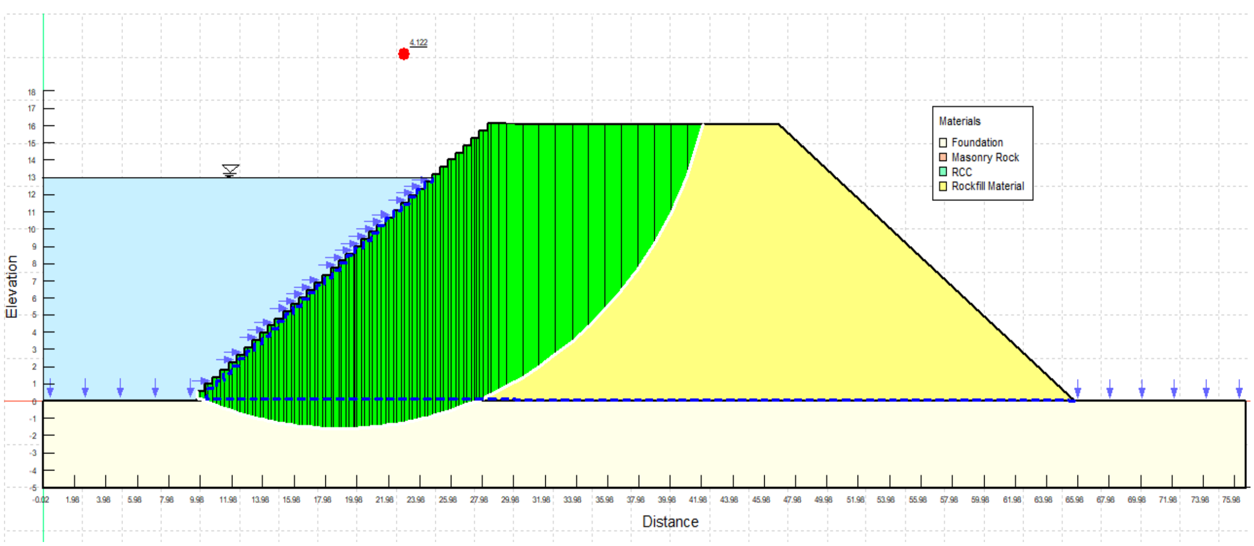
Peak Ground Acceleration (PGA): 0.025g

Horizontal Seismic Coefficient (Kh): 0.0125

The analysis incorporated these pseudo-static forces to simulate earthquake loading. The results confirm that the embankment maintains a stable profile during seismic events, satisfying the USACE (2003) minimum required safety factor of 1.1.

Figure 21 presented the results of the pseudo-static slope stability analysis performed on the upstream slope under seismic loading conditions. Utilizing the limit equilibrium method to identify the critical slip surface, the analysis yielded a Factor of Safety (FOS) of 4.122.

This calculated value significantly exceeded the typical minimum required safety factors for seismic conditions (generally between 1.0 and 1.2). This result confirmed that the upstream embankment maintained robust stability and exhibited ample resistance against potential failure



during seismic events.

Figure 22 illustrated the results of the pseudo-static slope stability analysis for the downstream slope under seismic loading conditions. The analysis, which utilized limit equilibrium methods to identify the critical slip surface, determined a Factor of Safety (FOS) of 1.477.

This value exceeded the typically recommended minimum safety factor for seismic loading (often ranging from 1.0 to 1.2 according to USACE guidelines). This finding indicated that the downstream embankment possessed adequate shear strength to resist failure during seismic events, maintaining a stable profile even under earthquake-induced forces.

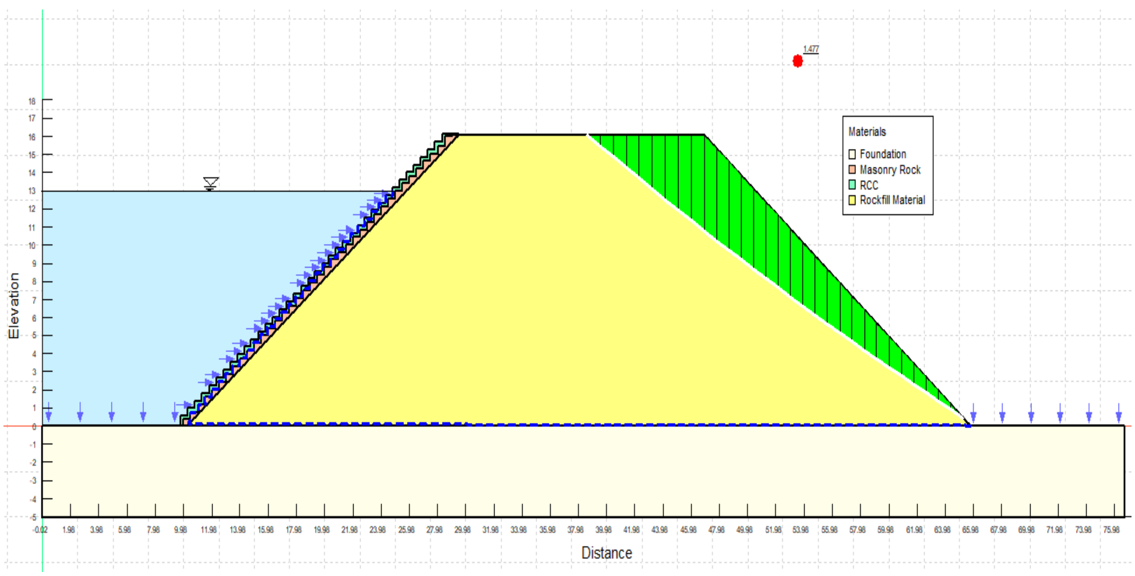


FIGURE 21 FOS for Downstream at Seismic Condition

Table 6 presented the summary of the slope stability analysis under seismic conditions for both the upstream and downstream slopes. As illustrated in Figure 22, the downstream slope exhibited a critical Factor of Safety (FOS) of 1.477, which was consistent across the Morgenstern-Price, Spencer, and Bishop methods.

Similarly, the upstream slope (previously shown in Figure 21) demonstrated high stability with an FOS of 4.122. Both calculated safety factors exceeded the minimum USACE (2003) requirement of 1.1, confirming the dam's stability under seismic loading.

Table 6 Slope Stability under Seismic Conditions

Loading Condition	Slope Stability under Seismic Conditions			States
Method of analysis at	Morgenstern price	Spencer	Bishop	
FOS at Critical analysis				
U/S	4.122	4.132	4.227	Ok
D/S	1.477	1.477	1.477	OK
Minimum Required Factor of Safety USACE, 2003	1.1	1.1	1.1	

4.3 Deformation analysis

The deformation and stress analysis evaluated the mechanical behavior of the embankment dam. The simulation assessed the structural response under self-weight and hydrostatic loading conditions, focusing specifically on vertical settlement, lateral deformation, and internal stress distribution. These parameters were analyzed to verify the overall stability of the dam and to ensure that potential displacements remained within safe operational limits.

Figure 23 presents the vertical displacement results, illustrating the settlement behavior of the embankment dam under the applied loads. The analysis revealed a maximum vertical settlement of approximately 0.024 m (2.4 cm), which corresponds to approximately 0.15% of the dam height. This value falls well within the standard theoretical range of 0.1% to 1.0% for well-compacted rockfill as established by Steffen et al. (2014).

As indicated by the blue contours, this settlement was concentrated near the dam crest and extended toward the upstream slope. This settlement profile is consistent with the consolidation expected from the self-weight of the fill material and the hydrostatic pressure exerted by the reservoir. The contours showed a gradual decrease in settlement magnitude towards the toe of the dam; this confirms that the foundation provided adequate support, indicating that deformation was driven primarily by the compression of the embankment body itself rather than foundation movement.

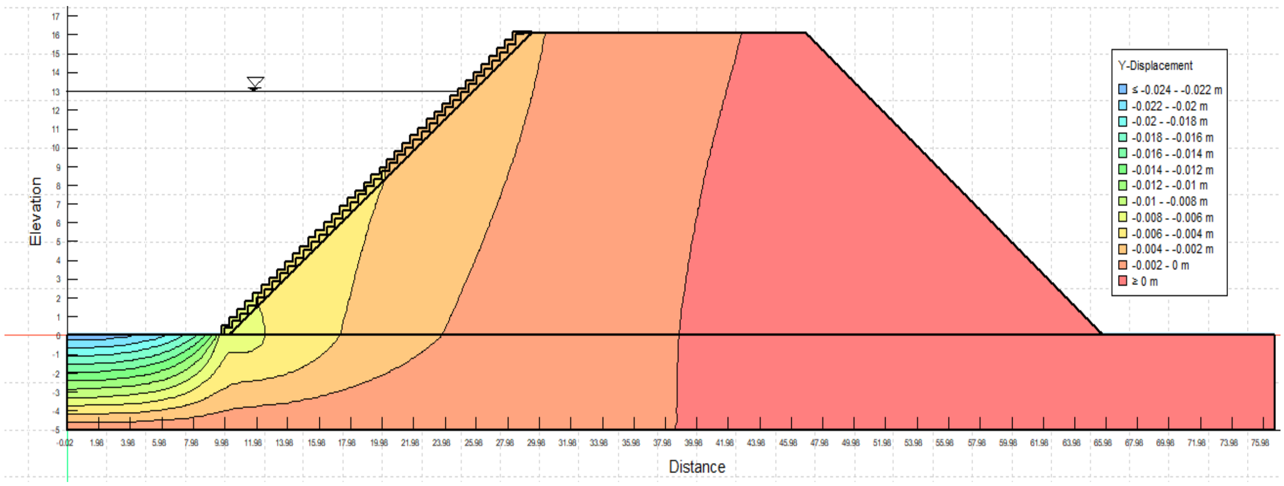


FIGURE 22 : Y-displacement

Figure 24 illustrated the horizontal movements within the embankment, highlighting the lateral spreading characteristics of the structure. The displacement contours displayed a divergent pattern: the upstream face exhibited negative displacement (moving left), while the downstream face showed positive displacement (moving right). The maximum magnitudes reached approximately 0.007 m. This behavior clearly demonstrated the Poisson effect, where the vertical compression of the soil mass induced slight lateral expansion. The relatively low magnitude of these horizontal displacements suggested that the embankment slopes were well-confined and stable, consistent with criteria for high shear stiffness (Cajon, 2006)

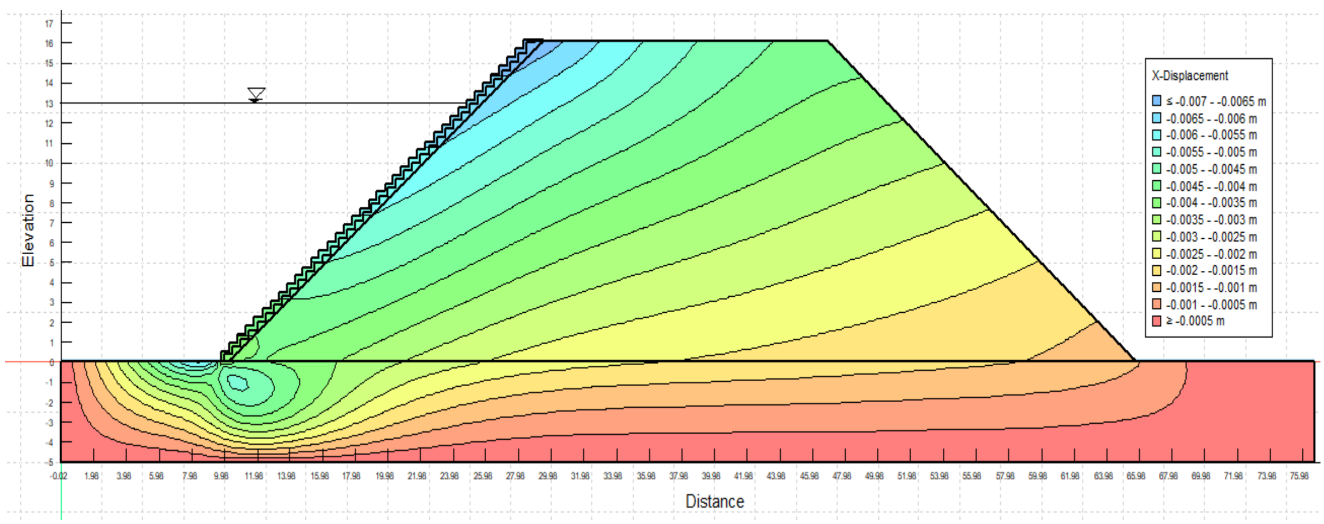


FIGURE 23 x-displacement

Figure 25 displayed the distribution of horizontal total stress across the dam section. The stress contours indicated a progressive increase in horizontal stress with depth, reaching maximum values exceeding 200 kPa at the base of the central core.

This distribution reflected the development of confining pressure within the embankment, which was essential for mobilizing the shear strength of the soil. The concentric nature of the stress bulbs implied that the core was effectively constrained by the surrounding shell materials, ensuring that sufficient lateral support was maintained throughout the depth of the structure.

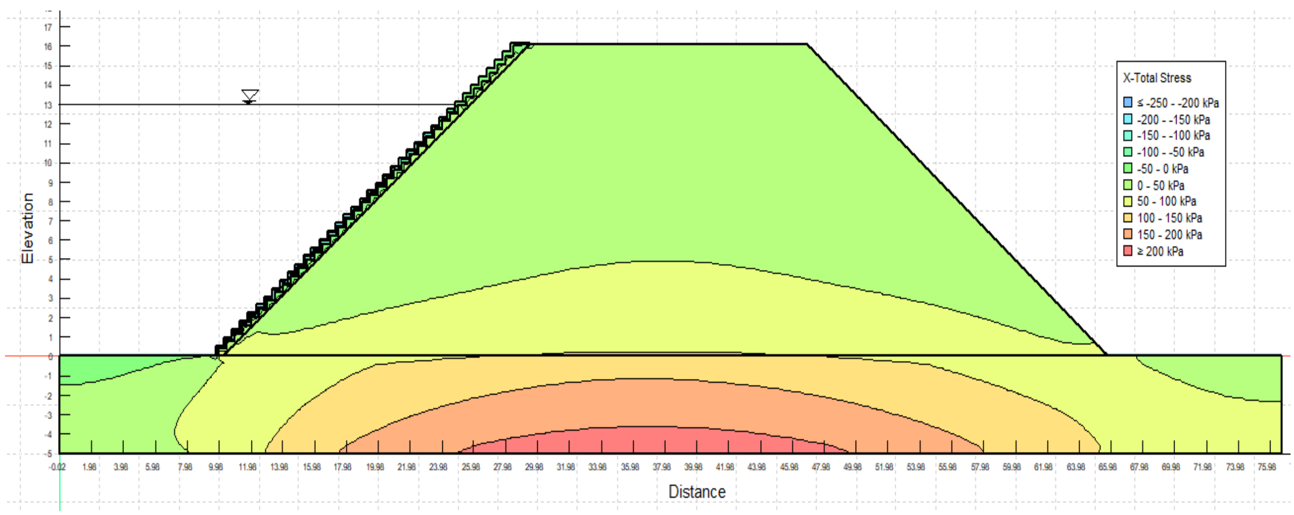


Figure 24 X - Total Stress

Figure 25 illustrated the vertical total stress distribution, a parameter primarily governed by the overburden pressure of the dam materials. The stress contours appeared as horizontal layers that increased linearly with depth, peaking at a maximum vertical stress of approximately 350 kPa at the interface between the dam and the foundation.

Notably, a slight asymmetry was evident on the upstream side, caused by the additional weight of the reservoir water acting on the slope. The regularity of these stress contours confirmed that gravity loading was correctly simulated; it further indicated that vertical load transfer to the foundation was uniform, thereby minimizing the risk of differential settlement.

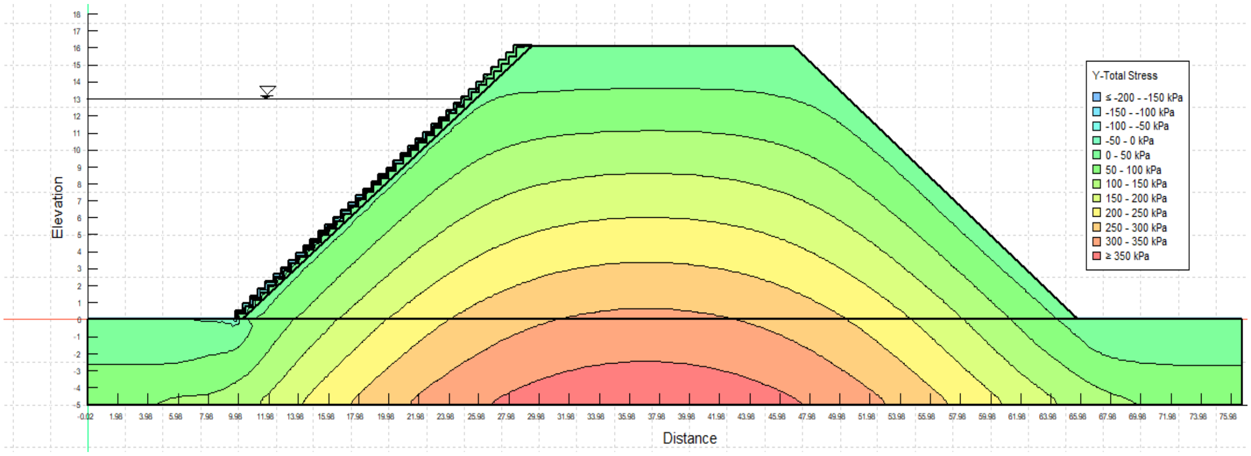


Figure 25 Y - total Stress

Figure 26 The Maximum Total Stress corresponds to the major principal stress acting within the embankment. Mirroring the vertical stress distribution, the major principal stress increased progressively with depth, reaching a peak value of 350 kPa at the foundation level. This result aligns closely with the standard theoretical criteria for overburden pressure which estimates a range of 340–360 kPa for a dam of this height (Fell et al., 2017)This parameter represents the maximum compressive force experienced by the soil elements and serves as the primary driver for both consolidation and shear stress development. The magnitude of these values, particularly when compared to the minimum total stress, confirmed that the dam was subjected to significant compressive loading; this state necessitated adequate frictional and cohesive strength within the fill material to maintain overall stability.

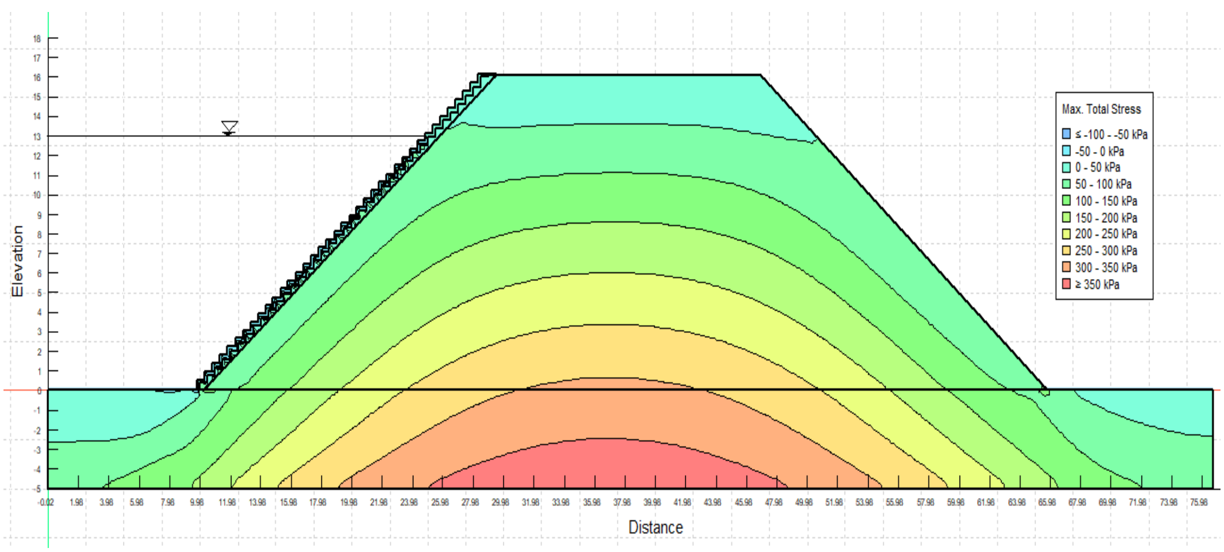


Figure 26 Maximum Total Stress

The Minimum Total Stress results, typically corresponding to the minor principal stress, were presented in Figure 27. The analysis showed that these stresses increased with depth, with the highest confining pressures located deep within the central portion of the dam

The values remained positive (compressive) throughout the section, peaking at approximately 200 kPa. This was a critical finding for dam safety: the total absence of negative (tensile) stress zones indicated that the risk of hydraulic fracturing or tensile cracking within the core was negligible, thereby ensuring the hydraulic integrity of the barrier.

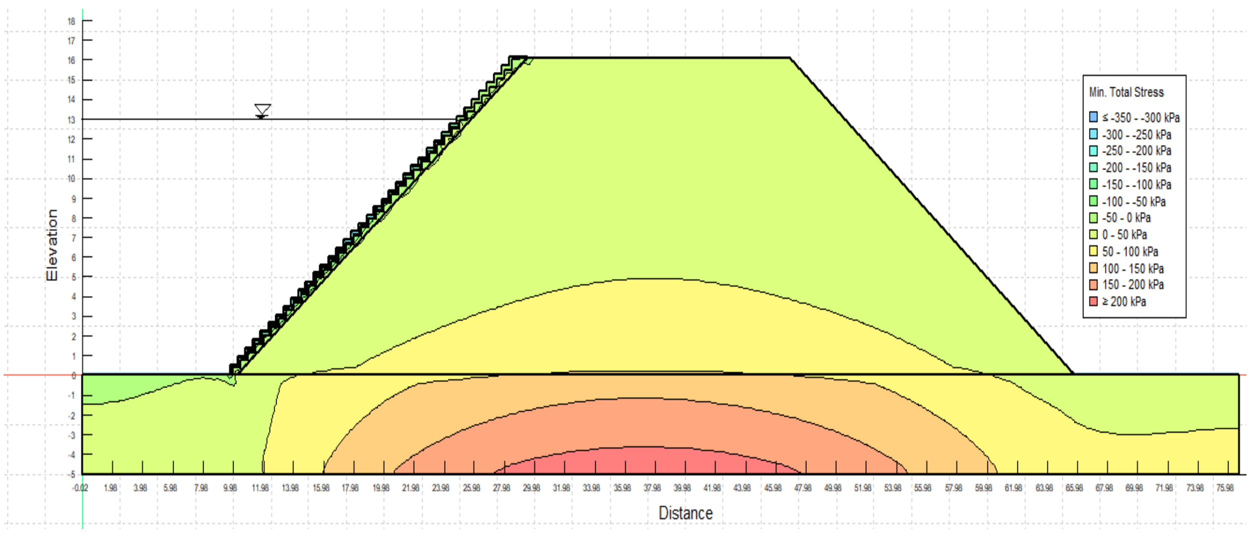


Figure 27 Min Total Stress

Table 7 : Current Analysis Results against Standard/Theoretical Values

Parameter	Analysis Result	Standard Criteria / Theoretical Value	Reference
Max Vertical Settlement (Smax)	0.024 m (approx. 0.15% of dam height)	0.1% – 1.0% of dam height (H) for well-compacted rockfill.	(Steffen et al., 2014).
Max Horizontal Displacement	0.007 m (7 mm)	Typically, < 20% of vertical settlement; indicates high shear stiffness.	(Cajon, 2006)
Max Total Stress (σ1)	350 kPa (at foundation level)	≈γ·H (20m3kN×17m≈340–360 kPa)	(Fell et al., 2017)

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter synthesizes the findings of the numerical modeling performed on the Bohol Qawlo Embankment Dam. It presents the final conclusions regarding the dam's geotechnical performance, specifically focusing on the trade-off between its structural stability and hydraulic vulnerability. Furthermore, it outlines practical engineering recommendations to mitigate identified risks and suggests directions for future research to enhance the long-term safety of hydraulic infrastructure in Somaliland.

5.2 Conclusion

The geotechnical investigation of the Bohol Qawlo Embankment Dam reveals a distinct contrast between its global structural stability and its internal hydraulic vulnerability. Structurally, the dam exhibits robust performance; the upstream and downstream slopes achieve Factors of Safety (FOS) of 2.279 and 1.490 respectively at the end of construction, significantly exceeding the USACE minimum requirement of 1.3. A peak seepage flux of 2.4× 10-4 m3/sec/m2 was recorded at the interface between the dam body and the colluvium foundation. Given the absence of a transition filter in the current design, this high-velocity flux presents a high risk of particle migration, internal erosion (piping), and progressive foundation washout. In contrast to the hydraulic vulnerability, the structural stability analysis demonstrated robust performance. Consequently, the installation of an engineered toe drain is strictly required to safely manage the high flux and prevent progressive foundation washout.

5.3 Recommendations

Recommendations Based on the findings of this study, the following practical engineering measures are recommended to ensure the long-term safety and operational sustainability of the Bohol Qawlo Embankment Dam:

1. Construction of an Engineered Toe Drain: Although the exit gradient is technically safe,

the high seepage flux of 2.4×10^{-4} $m^3/sec/m^2$ necessitates immediate seepage management. It is strongly recommended to construct a rock toe drain equipped with a properly graded inverted filter. This structure is critical to safely discharge seepage water without allowing the migration of fine particles from the colluvium foundation, effectively mitigating the risk of piping.

2. Verification and Enhancement of the Grout Curtain: The concentration of flux at the foundation interface suggests potential vulnerability in the cut-off system. The depth and integrity of the existing grout curtain should be verified. If field observations during reservoir filling indicate excessive leakage, extending the grout curtain depth into the foundation is recommended to lengthen the seepage path and reduce flux velocity.
3. Implementation of Instrumentation and Monitoring: To validate the numerical predictions and ensure early detection of anomalies, a robust monitoring program must be established. This should include the installation of vibrating wire piezometers at the downstream toe to monitor pore water pressures and settlement markers on the crest to track deformation over time.

5.4 Future Research Directions

To further advance the understanding of embankment dam performance in Somaliland's geological context, the following areas are suggested for future investigation:

1. Dynamic Liquefaction Analysis: The current study area located medium hazard level according the Global Earthquake Model (GEM) and Think Hazard while Somaliland still in the process of formalizing a national building code with specific "zone numbers my study relied on pseudo-static analysis, which simplifies earthquake forces. Future research should employ Time History Analysis (THA) using real accelerograms to specifically evaluate the liquefaction potential of the saturated sandy foundation under higher magnitude seismic events.
2. Three-Dimensional (3D) Stability Analysis: This study utilized a 2D plane-strain model. However, for dams situated in narrow valleys like the Bohol Qawlo site, 3D effects from the abutments can significantly influence stability. A 3D analysis is recommended to

provide a more accurate and potentially less conservative estimation of the Factor of Safety.

3. Probabilistic Sensitivity Analysis: Given the inherent variability of soil properties in semi-arid regions, future studies should incorporate probabilistic methods. A sensitivity analysis would help quantify how variations in critical parameters—specifically the hydraulic conductivity and internal friction angle of the sandy loam—impact the overall reliability of the dam.

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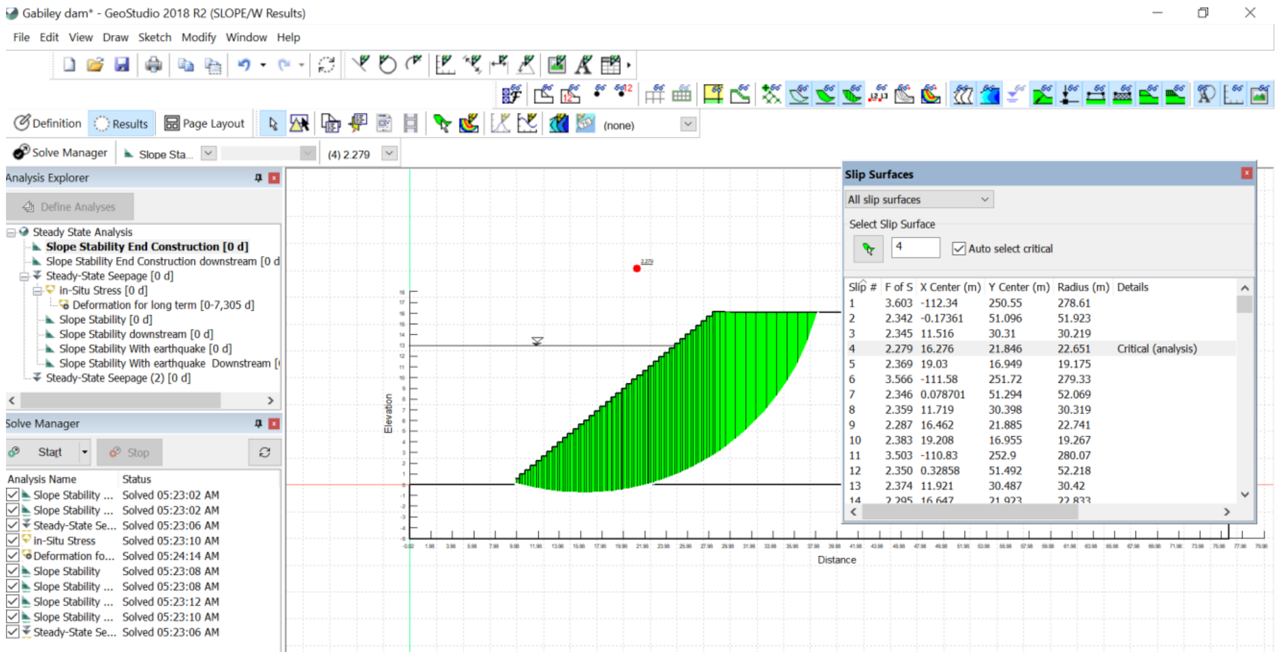
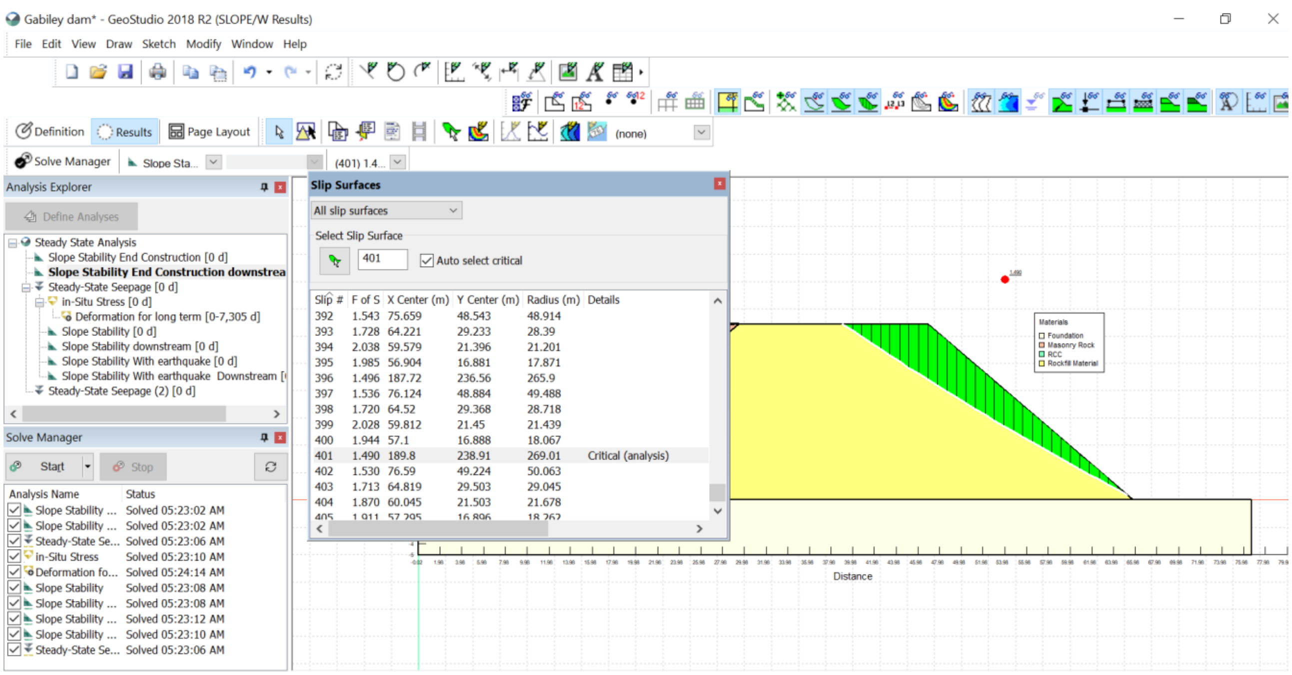
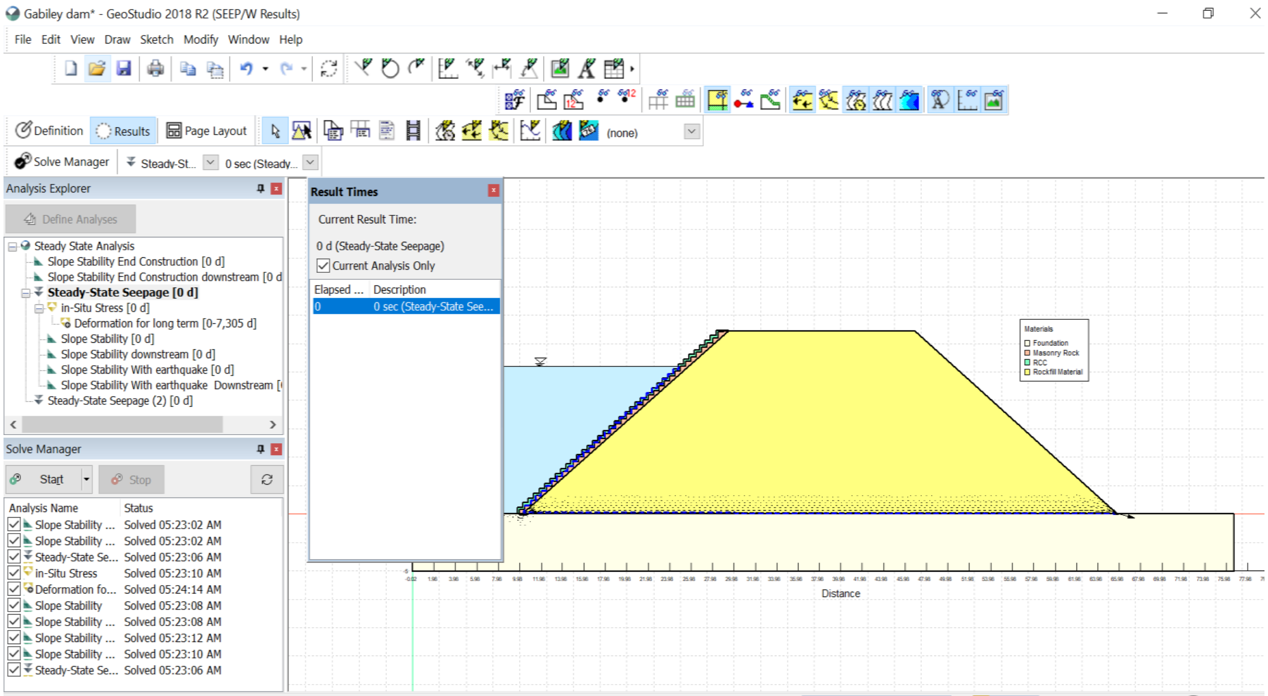
Appendix

Slope stability end of construction US/DS





Steady State Seepage analysis


Gabiley dam* - GeoStudio 2018 R2 (SEEP/W Results)
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Slope Stability End Construction downstream [0 d
Steady-State Seepage [0 d]
in-Situ Stress [0 d]
Deformation for long term [0-7,305 d]
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Slope Stability With earthquake Downstream [
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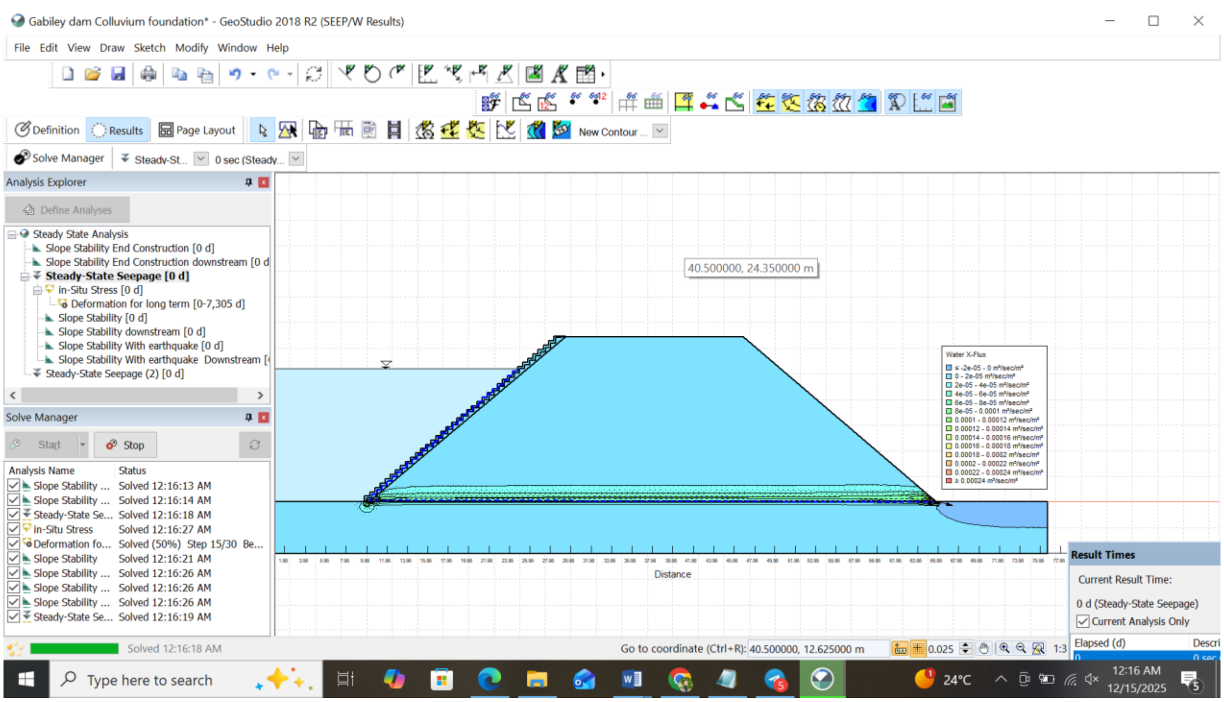
Gabiley dam Colluvium foundation* - GeoStudio 2018 R2 (SEEP/W Results)
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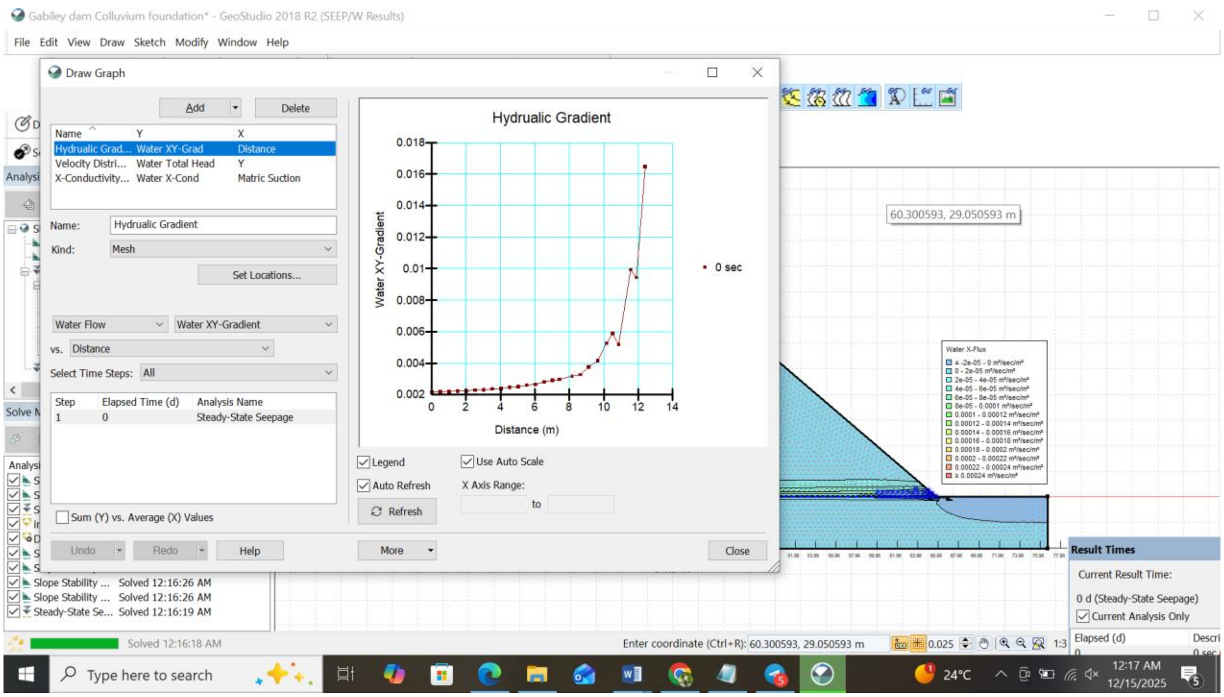

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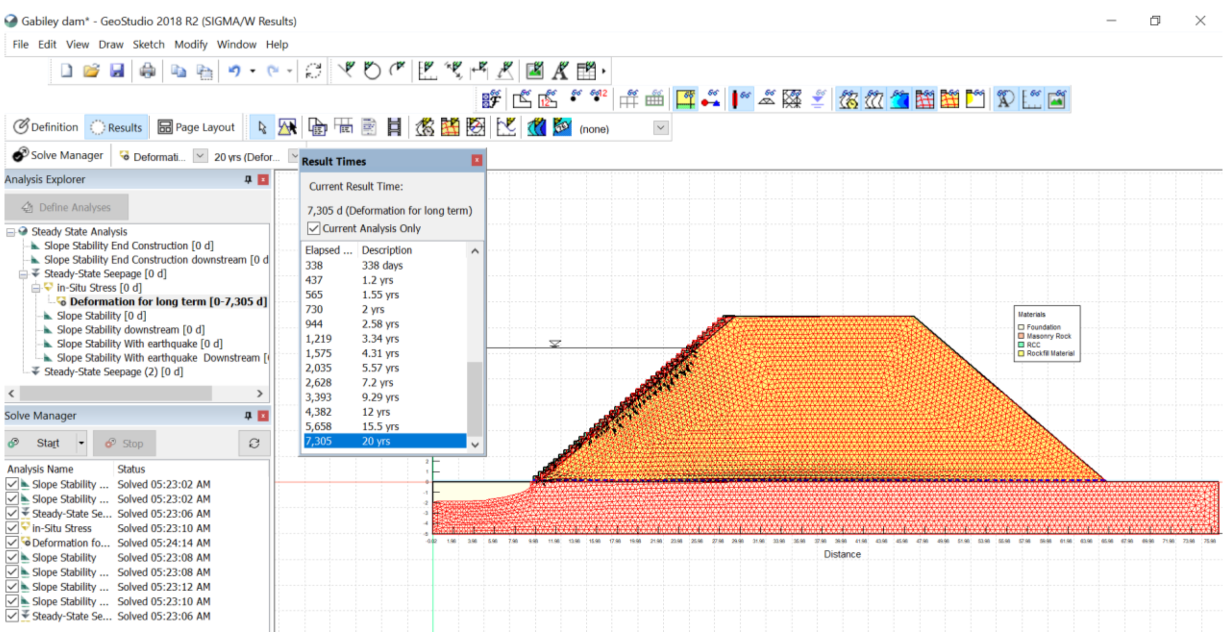
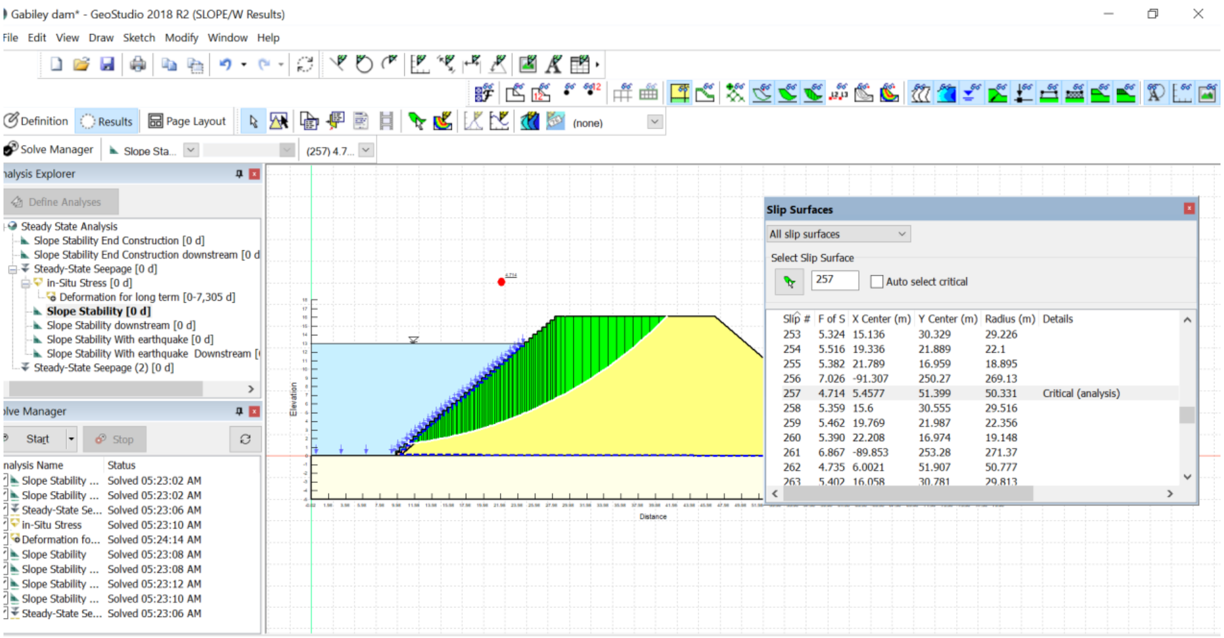
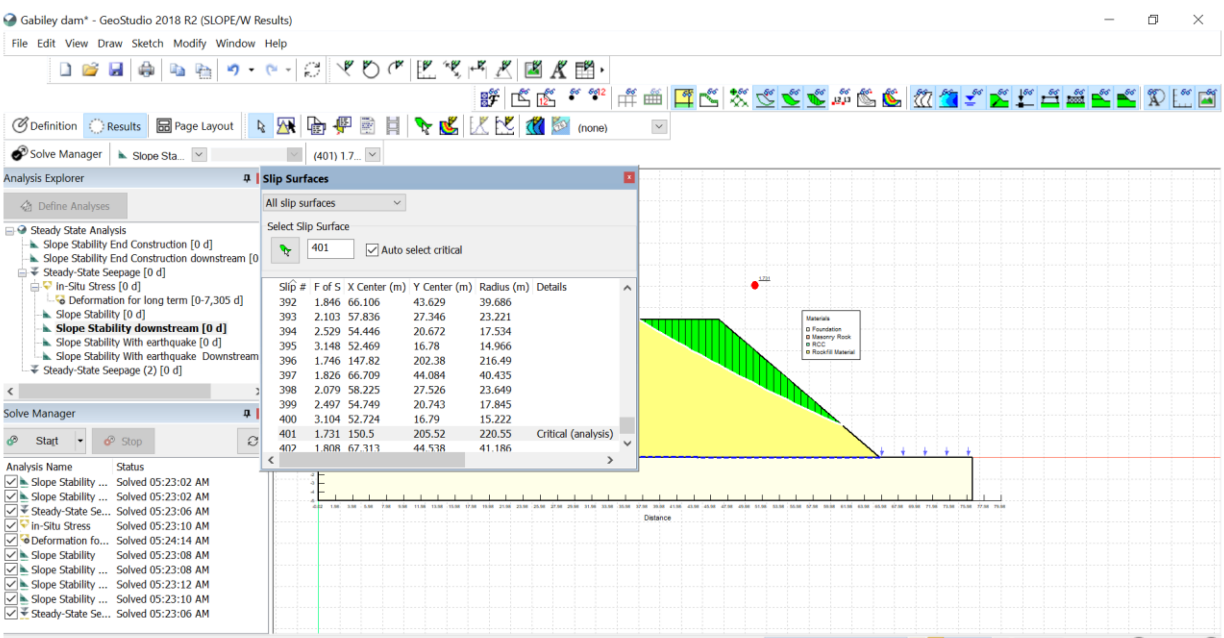
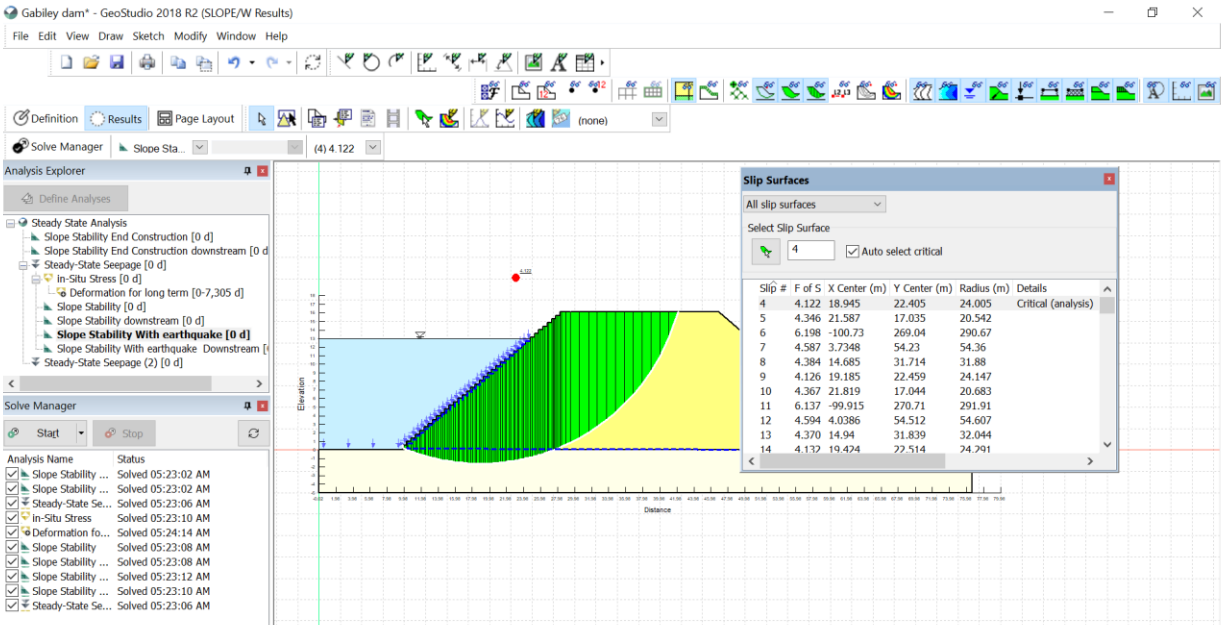


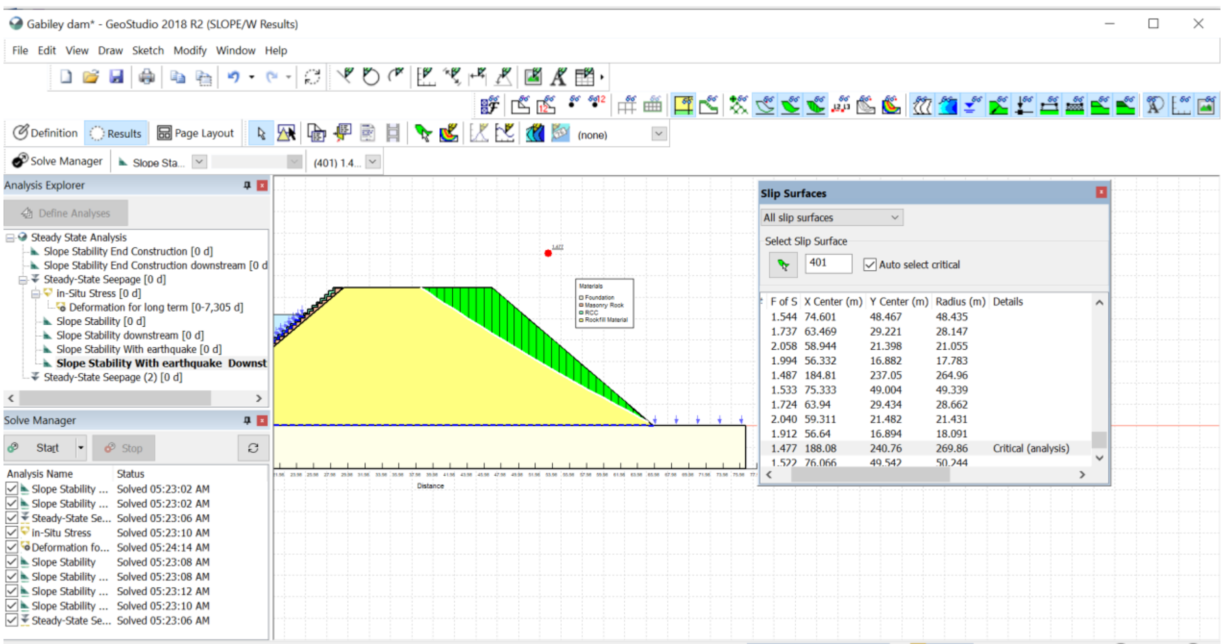
Long term slope stability analysis US/DS





Slope stability at seismic loading





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