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Seepage Analysis and Optimization of Reservoir Earthen Embankment with Double Textured HDPE Geo-Membrane Barrier

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Abstract

This research paper focuses on conducting a steady state seepage analysis along with the downstream slope factor of safety using the Modified Bishops method in a poorly compacted earthen embankment and optimizing the same reservoir earthen embankment in a case study located near Sadiyavav village in Junagadh district in Gujarat, India. The study site, situated at 21°32'06.5"N and 70°37'26.7"E, is renowned for its Asiatic lions. The analysis and optimization were performed with a double-textured High-Density Polyethylene (HDPE) Geo-membrane barrier. Previously, designs and numerical solutions proposed homogenous embankments and too poorly compacted with no drainage arrangements, which led to anisotropic conditions within the section and water seeping out, cutting the phreatic line. The paper presents the documented improvements in the factor of safety achieved through the seepage analysis and the optimization of the HDPE Geo-membrane barrier. Two improvement techniques were studied using the "Limiting Equilibrium-Finite Element Method" (LS-FEM). The first using (HDPE) Geo-membrane stabilized with gabions, and the second alternative using HDPE Geo-membrane with gabions in addition to rock toe. The study results showed improvements in the downstream slope stability for the two alternatives by 3% and 10%, respectively.

Keywords: Earthen Embankment; Seepage Analysis; High Density Polyethylene (HDPE) Geo-membrane; FEM Optimization; Seepage; Bed/Slope Stability; Factor of Safety (FOS).

1. Introduction

Constructing an earthen dam embankment proves to be a more cost-effective alternative for water storage when compared to a gravity dam [1]. However, it is crucial that the available materials at the construction site meet the requirements of strength and permeability for the earthen dam embankment [2, 3]. The most important step in the construction of an earthen embankment is the compaction of the earth to be used in the bed and slope in the proper line and level. However, due to a lack of proper confinement near the slopes and poor compaction control, results in

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anisotropic channel formations in the earthen dam itself. This leads to a more or less "parallel plate arrangement" in the existing soil embankment and a more free path for the water to flow. Alternatively, if the site lacks cohesive soil or if the soils possess high permeability, the embankments must be designed using artificial waterproofing barriers. The failure of the downstream slope primarily occurs due to excessive water seepage through the embankment, leading to slope failure, toe failure, and deformation of the downstream side of the dam. These issues are commonly encountered at construction sites due to anisotropic soil conditions and inadequate compaction of the embankment.

In recent times, the utilization of polymeric materials, such as geo-synthetics, has gained widespread acceptance and is being extensively applied in various fields due to their sustainable attributes [4, 5]. Incorporating geo-synthetics in engineering not only enhances the resilience of structures but also contributes significantly to the achievement of the United Nations Sustainable Development Goals (UNSDGs). One widely employed geo-synthetic material is HDPE (High-Density Polyethylene) Geo-membrane, which finds extensive use as a cover for landfills to mitigate rainwater leaching, as a collection system for leachate and landfill gas, and as a bottom barrier system to prevent soil and groundwater contamination [6, 7]. Additionally, these materials are favored for their durability, excellent UV resistance, and relatively low cost. More recently, the use of geo-membranes in the construction of earthen dams and lining ponds and canals has gained prominence as a primary and/or secondary measure to reduce seepage.

The utilization of geo-membranes in earthen dams offers several benefits, including the reduction of piping phenomena and the prevention of soil particle erosion when exposed to water [6, 8]. Furthermore, geo-membranes can be employed to rehabilitate older earthen dams, effectively mitigating downstream slope failure caused by piping or gully formation. One advantage of incorporating geo-membranes in earthen dams is the reduction in the length of the phreatic line. This study specifically focuses on the use of 1.0 mm HDPE geo-membrane as a barrier on the upstream slope of an earthen dam under constant reservoir water height, various seepage conditions, failure scenarios, with or without gabions, and with or without a rock toe.

Geo-membranes find widespread use in civil and environmental engineering projects as impermeable barriers to prevent fluid migration, such as seepage or pollution, in various applications, including landfills, mining sites, reservoirs, and containment ponds [9–12]. The correct design and installation of geomembranes are essential to ensuring their long-term effectiveness in providing containment and environmental protection [13]. However, it is crucial to carefully consider and optimize the intricate interaction between geo-membranes and the underlying soil to achieve optimal performance [14].

The performance and behavior of the Geo-membrane system are significantly influenced by the interaction between the soil and the geo-membranes. Typically, geo-membranes are placed on the surface of the soil, acting as a barrier against fluid migration [15, 16]. Various factors, such as soil type, soil compaction, slope angle, external stresses, and temperature fluctuations, impact the behavior of the soil-geo-membrane system [16]. When a geo-membrane is installed on the soil, it experiences mechanical interactions with the soil. The load imposed on the system, such as the weight of the soil or other external loads, results in stress distributions within both the geo-membrane and the soil. These stresses are transmitted between the geo-membrane and the soil, influencing their respective behaviors [17].

The shear strength and frictional properties of the soil-geo-membrane interface play a crucial role in determining the stability and performance of the system. The interface's shear resistance is influenced by factors such as the roughness of the geo-membrane surface, soil properties, and the level of soil compaction. Insufficient soil compaction or irregularities on the geo-membrane surface can decrease the shear strength of the interface, potentially leading to slippage or failure along the interface [18, 19]. External stresses, such as surcharge loads and hydrostatic pressure, also impact the behavior of the soil-geo-membrane system. These loads introduce additional stresses on both the geo-membrane and the soil, altering their behaviors and interactions. Considering these loads and their effects is vital to preserving the integrity of the geo-membrane and preventing undesired deformations or collapses [20].

The application of the Finite Element Method (FEM) analysis enables projects to simulate and analyze the mechanics of soil-geo-membrane interaction with a high level of detail and accuracy [21]. FEM allows for the creation of computational models that represent the soil-geo-membrane system, taking into account factors such as soil properties, geo-membrane properties, boundary conditions, and various loading scenarios. Through FEM analysis, deformations and displacements within the geo-membrane system can be simulated. This information is crucial for assessing the structural integrity of the barrier and identifying areas of excessive deformation that may lead to failure or reduced effectiveness in containing fluids. By evaluating and minimizing deformations, engineers can improve the performance and durability of the geo-membrane barrier, thereby reducing the potential risk of environmental hazards. These simulations also enable the evaluation of stress distribution, deformation patterns, and failure mechanisms within the soil-geo-membrane system, aiding in the optimization of design and placement strategies [22].

Assessing and controlling seepage is another vital aspect of designing a geo-membrane barrier, and utilizing FEM analysis enables the evaluation of seepage characteristics within the system. These characteristics encompass seepage pathways, flow rates, and pressure distributions [23]. By comprehending seepage patterns and assessing the barrier's effectiveness in limiting fluid migration, engineers can enhance the design of the geo-membrane barrier to reduce the risks associated with contamination or erosion [24]. Seepage conditions are influenced by several factors, including the hydraulic properties of the soil, geo-membrane design, and boundary conditions of the system. The hydraulic conductivity of the soil, which measures its ability to transmit water, plays a crucial role in determining the extent of water loss through seepage. Factors such as fine particles, heterogeneity, and soil compaction affect the soil's permeability and seepage behavior [25]. Additionally, the design and characteristics of the geo-membrane play a significant role in seepage mitigation. Geo-membranes are typically selected for their impermeable properties, but their effectiveness can be influenced by variables such as thickness, material type, and the presence of defects or damage. Ensuring proper selection and installation techniques of the geo-membrane are essential to minimize the potential for seepage [26].

Seepage within the soil-geo-membrane system is greatly influenced by the surrounding boundary conditions. External factors such as groundwater levels, hydraulic gradients, and applied loads have an impact on the direction of seepage, flow rates, and pressure distribution within the system. A significant hydraulic gradient, for example, can lead to higher seepage velocities that can compromise the integrity of the geo-membrane system [27]. Effective management of seepage issues in soil-geo-membrane applications requires a comprehensive understanding of the hydraulic behavior of the system. Uncontrolled seepage can have significant consequences, including contamination of nearby soil and groundwater, slope instability, and failure of containment structures [28]. To mitigate these issues, it is crucial to have a deep understanding of the hydraulic behavior of the system. Failure to address seepage problems adequately can result in severe consequences, such as the contamination of neighboring soil and groundwater, slope instability, and structural failure of containment systems [29, 30].

Furthermore, numerical modeling techniques such as the Finite Element Method (FEM) analysis have proven to be highly valuable in the analysis and management of seepage scenarios within soil-geo-membrane systems [31]. By considering the complex interactions between soil, geo-membrane, and boundary conditions, FEM analysis allows for the simulation of fluid flow throughout the system. These models provide valuable insights into seepage patterns, flow velocities, and pressure distributions, enabling the optimization of design parameters and the identification of potential seepage risks [32].

Ensuring the stability of the upstream slope of an embankment is of utmost importance. By utilizing FEM analysis, it becomes possible to analyze the interaction between the soil, geo-membrane, and external factors such as pore pressure and slope geometry [33]. Through the examination of these parameters and their influence on slope stability, FEM analysis aids in designing reinforcement measures that enhance the overall stability and performance of the embankment [34]. Furthermore, FEM analysis allows for the optimization of various design parameters of geo-membrane barriers, including thickness, reinforcing techniques, slope angles, and anchoring methods [35, 36]. By simulating and evaluating the impact of these parameters on the performance of the geo-membrane barrier, FEM analysis facilitates informed decision-making to achieve the desired level of containment and stability [37]. Additionally, FEM analysis enables the identification and prediction of potential failure mechanisms and modes within the geo-membrane system. By considering excessive stresses, deformations, and localized failures, engineers can anticipate failure scenarios and modify designs to mitigate risks. This proactive approach reduces the likelihood of unforeseen failures, enhances the reliability of the geo-membrane barrier, and ensures the long-term integrity of the embankment [38].

The objective of this study is to implement a 1 mm HDPE (High-Density Polyethylene) geo-membrane with a double-textured surface as an efficient barrier on the upstream slope of an embankment. This problem has been chosen for a numerical study due to its strategic influence on the locality in terms of water supply and power generation. The selection of this particular geo-membrane was driven by the observation of a phreatic line intersecting the downstream slope, which was attributed to anisotropic conditions resulting from inadequate compaction of the embankment material during construction. To address this issue, the project aims to deploy the double-textured HDPE geo-membrane to restrict water migration across the embankment, thereby reducing the potential risks of slope failure caused by seepage and soil erosion. This chosen geo-membrane not only serves as a protective measure but also offers enhanced impermeability, stability, and durability, which are crucial for ensuring the long-term performance of the embankment structure. Previously, designs and numerical solutions proposed homogenous embankments and too poorly compacted with no drainage arrangements, which led to anisotropic conditions within the section and water seeping out cutting the phreatic line [34-37]. Geo-membranes can have either a smooth or textured surface. They are thin, flexible sheets made of thermoplastic polymeric materials. The determination and measurement of geo-membrane thickness depend on the surface characteristics. In the case of smooth or non-textured geo-membranes, a single value can be used to describe their thickness, with only minor variations resulting from the manufacturing process. However, for textured geo-membranes, which have raised areas on one or both sides to enhance friction with adjacent layers, the thickness cannot be defined as a single value. Instead, the core thickness and the heights of the raised areas (asperities) need to be measured separately [39].

Geo-membranes are increasingly being used as waterproofing coatings in granite dams and earth due to their numerous advantages over traditional barrier materials, including impermeability, cost-effectiveness, practicality, and ease of construction. Typically, a geo-membrane barrier system for such applications consists of three layers: the geo-membrane barrier itself, the basal support layer, and the protection cover layer. In Chinese design specifications for rolled earth-rock fill dams, the geo-membrane barrier usually comprises a single layer of HDPE or PVC geo-membrane and two non-woven geotextile layers. The complex geo-membrane is bonded to the surface of the support layer [40].

For elevated earth dams, a wedge-shaped protection cover is commonly employed to enhance the stability of the barrier system. However, the interface between the protection cover soil and the composite geo-membrane often serves as the preferred failure surface due to the low shear strength of this interface. Therefore, the design of the geo-membrane surface barrier in an earth dam must consider the stability of the wedge-shaped protection cover. Girard et al. [41] reported a slide failure of a protection cover along the interface between the geo-membrane and geotextile in an embankment. Investigation and analysis revealed that the incident occurred due to an overestimation of dynamic stresses and the interface shear strength resulting from vehicle traffic.

Assessing the stability of geo-membrane barriers is of utmost importance in the design of barrier systems. This aspect has been extensively examined by various researchers, as evident from the existing literature. The studies primarily focus on two key aspects. Firstly, they investigate the shear strength properties and interface parameters of geo-synthetics. Secondly, they explore methodologies for analyzing slope stability in geo-synthetic barrier systems [42].

The geo-synthetic interface shear strength plays a critical role in ensuring the integrity of a geo-synthetic barrier along a slope. The shear strengths at the interface between the geo-synthetic and the soil on the base and slope are the primary contributors to the resistance against failure of the geo-synthetic barrier system. Therefore, determining the appropriate limits for interface shear strength is essential for assessing the integrity of the geo- synthetic barrier. Typically, a series of laboratory or site-specific experiments are conducted to obtain the interface strength parameters. Dixon et al. [43] provided recommendations for deriving characteristic shear strength values of geo-synthetic interfaces from a limited number of tests. However, Dixon et al. [43] observed that the conventional practice of deriving interface strength parameters does not adequately capture the variability of interface strength for design purposes. They proposed a comprehensive analysis of measured strengths and an evaluation of variability. When considering literature and internal database variability values, relatively high failure probabilities were obtained through reliability analyses. While using repeatability data reduces probabilities for commonly employed safety factors, these probabilities still exceed the suggested target values for failure likelihood. Sia and Dixon [44] found that the normal distribution is suitable for representing their derived strength and interface shear strength parameters, especially when variability is modest. Their calculations and comparisons led them to the conclusion that incorporating uncertainty and variability based on inter-laboratory and global datasets leads to overly conservative design outcomes.

Geo-membranes are currently being employed in a wide range of extensive coating applications. These include reservoirs, dikes, dams, various containment basins like leaching ponds or tailings ponds in ore processing and mineral extraction, landfill capping and basal liners, as well as sealing large areas to safeguard and confine hazardous materials [45]. Furthermore, geo-membranes find utility in diverse areas such as remediation of contaminated land, construction of tunnels and canals, installation of large-scale connecting liners in road construction, and industrial facilities. In the United States, there is extensive use of geo-membrane liners for containing hazardous waste in basins [46]. Jones & Dixon [47], introduced a methodology to assess the stability and structural integrity of geo-synthetic barrier systems. They proposed a modeling approach that considers the softening-strain behavior of geo-synthetic interfaces, enabling the evaluation of localized failures within the barrier system. Furthermore, they explored the use of numerical analysis and limit equilibrium methods to assess the stability of the lining system, specifically focusing on strain softening interfaces. Chau et al. [48], studied a landslide occurred in Nhan Co. Industrial Zone, Dak Nong, Vietnam in April 2020, their FEM models assured that the rainfall seepage through the slope was the main cause of failure and they recommended to construct an underground drainage using (HDPE) geo-membrane.

Kumar and Roy [49], reported three case studies of a slopes reinforced with fibers. Two of them were reinforced by natural fibers (Jute fibers), while the third one was reinforced by hybrid fibers of (HDPE, Jute fibres and coconut fiber). The comparison between the three cases showed the superior behavior of the hybrid fibers. The efficiency of HDPE geo-membrane depends on the construction quality control, the existing of roll-direction and cross-roll-direction wrinkles can significantly reduce the efficiency [50]. Also, the impact of hydro-geotechnical conditions of the shear strength of the soil, its interface with adjacent geo-martials and the global stability of slopes were investigated by Mehmood et al. [51], there research showed a significant reduction on both shear strength and interface capacity with increasing the water content. Finally, Louw [52], strongly recommended to measure the shear strength at the interface between (HDPE) and the adjacent soil experimentally. In his research, he compared the stability factor of safety of a slope using the measured values and the recommended ones by the manufacture, and he concluded that the results of the measured strength were significantly lower than the manufacture values.

2. Study Objective

Although conventional global stability analysis using safety factors is applicable, their findings demonstrated that settlement of refuse can cause components of the coating to slide down the slope. They suggested that traditional limit equilibrium methods are inadequate for evaluating localized failures within geo-synthetic lining systems. Based on Jones's study, it can be concluded that (1) mathematical analysis techniques can effectively capture the interactions involved, and (2) when considering the softening- strain behavior of geo-synthetic interfaces in landfill coating systems, the limit equilibrium technique may overestimate the safety factor along a slope. Hence, the main objective of this study is to evaluate the enhancing in the stability of earthen dams constructed using HDPE geo-membrane using a hybrid technique of "Limiting Equilibrium - Finite Element Method" (LS-FEM). In order to achieve the previous objective, the shown methodology in Figure 1 was considered.

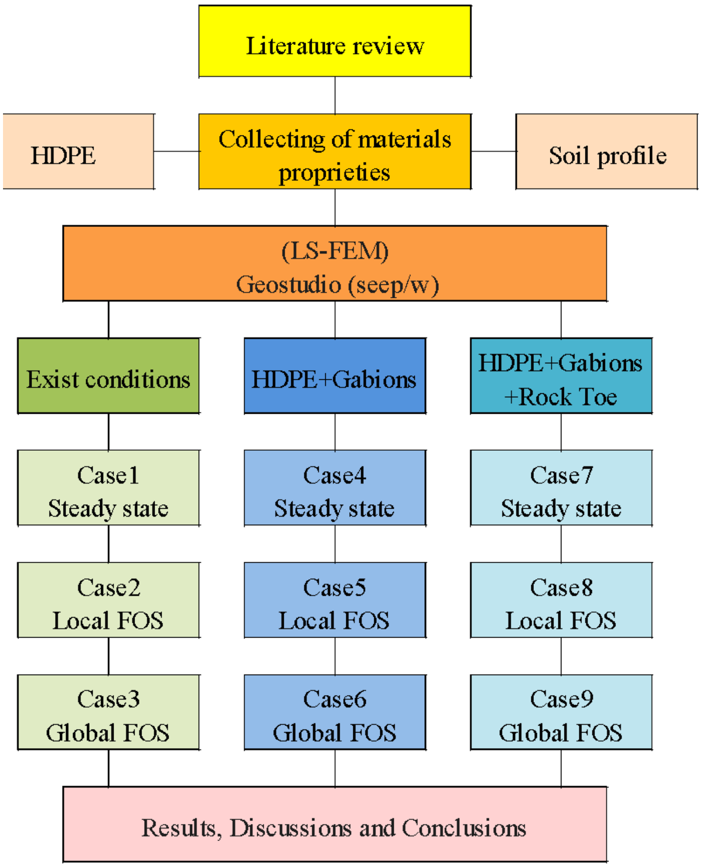


Figure 1. The considered methodology

3. Research Methodology

3.1. Case Study and Description of Problem

The Sadiyavav Irrigation Tank, also known as the Pashwada Dam Site, is a percolation tank situated near Sadiyavav village in the Junagadh district of Gujarat, India. It is located at coordinates 21°32'06.5"N 70°37'26.7"E, in close proximity to the Gir forest renowned for its Asiatic lions. Figure 2 displays pictures and a site map of the area. The primary purpose of a percolation tank, such as the Sadiyavav Irrigation Tank, is to replenish the groundwater table in the vicinity, thus serving as a vital source of groundwater supply. The tank plays a crucial role in indirectly providing water to the local tribes residing in the village. The central concept behind this percolation tank revolves around the natural movement of stored water into the ground under the influence of gravity. Geologically, the area consists of different layers, with the strata primarily comprising fine sand and silty-clayey sand up to a depth of approximately 3 meters, followed by a layer of coarse sand. This soil profile creates favourable conditions for the percolation of water stored in the reservoir. As the Sadiyavav Irrigation Tank is a percolation tank, there are no canals or canal structures associated with the project. However, a significant amount of water is retained in the reservoir due to the bunds constructed around the periphery of the scheme, effectively forming a storage facility.

Figure 2. Pictures from and Site Maps of the Pashwada Dam Site near the Sasan gir Forest (Asiatic Lions), Gujarat, India on 21°32'06.5"N 70°37'26.7"E

The embankments surrounding the project were constructed in the mid-90s using locally available material, specifically silty clayey sand. Due to the abundance of this material, a uniform section was chosen for construction. However, over time, inadequate maintenance, lack of repairs, and aging have led to the emergence of several issues. One notable problem is the abnormal flow of water observed passing through the downstream slope of all the embankments surrounding the reservoir. In response, a team of competent engineers from the state water resources department under the Government of Gujarat, India conducted a site visit. The issue of abnormal seepage through the downstream slope has raised concerns among the local residents and politicians alike. The team investigated the embankments and following observations were made:

- The embankment sections had an average height of 3 meters, with some sections reaching as high as 7 meters. However, crucial geotechnical features such as toe drains, outfall drains, longitudinal drains, and surface drains were completely absent.
- Visible signs of settlements, such as bulging and concavities, were observed on the top of the embankments. These signs clearly indicated poor compaction during the construction phase, leading to subsequent distress.
- The presence of anisotropic conditions in the sections indicated inadequate workmanship and compaction. Some layers may have been compacted while others remained un-compacted during placement, resulting in gradual settlement and the formation of micro channels within the sections.
- During the peak monsoon period, when water accumulated up to the designated high flood level, the water pressure led to steady seepage through these channels. The lack of proper drainage facilities resulted in the phreatic line remaining unconfined within the embankment structure.

3.2. Materials Characteristics, Specifications, Sampling/preparation and Placement Method

The selected material for the embankment's upstream slope is a high-quality double-textured 1 mm HDPE Geo-membrane. The decision to use this Geo-membrane was driven by the presence of the phreatic line intersecting the downstream slope, which was caused by anisotropic conditions resulting from poor compaction during the embankment construction. The HDPE Geo-membrane is manufactured using virgin high-density polyethylene resin, ensuring a superior quality product that is free from plasticizers or fillers. It exhibits a consistent color, texture, and finish, without any pinholes, undispersed raw materials, streaks, or foreign particles. It is also free from visible defects such as melt fractures, holes, tears, or blisters. The specified thickness of the HDPE Geo- membrane complies with the requirements outlined in IS 16352 (2020) [53] and meets the characteristics described in Table 1.

Table 1. Characteristics of Double side Textured Geo-membrane for respective thickness

#	Characteristics	Thickness (mm)						Method of Test
		0.75	**1.00**	**1.50**	**2.00**	**2.50**	**3.00**	
1	Average core thickness, mm	0.75 (-5 %)	1.00 (-5 %)	1.50 (-5 %)	2.00 (-5 %)	2.50 (-5 %)	3.00 (-5 %)	ASTM D 5199 (2019) [54]
2	Hydrostatic Resistance	No leakage at 10 kg/cm^2	No leakage at 15 kg/cm^2	No leakage at 25 kg/cm^2	No leakage at 35 kg/cm^2	No leakage at 40 kg/cm^2	No leakage at 45 kg/cm^2	ISO 811 [55]
3	Tear resistance, N (minimum)	93	125	187	249	311	374	IS 14293 (1995) [56]
4	Puncture resistance, N (minimum)	200	267	400	534	667	800	ASTM D 4833 (2020) [57]
5	Yield strength, kN/m (minimum)	11	15	22	29	37	44	ASTM D 4595 (2017) [58]
	Yield elongation% (minimum)	12	12	12	12	12	12	
6	Breaking strength, kN/m(minimum)	8	10	16	21	26	32	
	Breaking elongation, % (minimum)	100	100	100	100	100	100	
7	Carbon black content, %	2.0 to 3.0						IS 2530 [59]

The Engineer in Charge directed the performance of confirmatory tests on the supplied HDPE Geo-membrane. The collection of samples for these tests followed the procedures outlined in Table 2. The collected samples were then tested at specified laboratories, namely ATIRA, GIRDA, BITRA, and CIPET, in the presence of a representative from the Department. The contractor was responsible for arranging and covering the cost of sample transportation to the respective laboratory to ensure prompt confirmatory testing. The contractor also liaised with the laboratory to determine the test facilities available and the expected time for test results. Once confirmed by the Engineer in Charge, the samples were dispatched with proper identification. Only the HDPE Geo-membrane lot/quantity that met the test requirements during the confirmatory tests was used for the project. The remaining rolls of HDPE membrane were promptly removed from the work site.

Table 2. Sample size and criterion for conformity for rolls (IS 16352:2020) [53]

S/N	No. of rolls in the lot	No of rolls to be selected	Permissible no. of defective rolls
i)	Up to 50	3	0
ii)	51-150	5	0
iii)	151-300	8	0
iv)	301 and above	13	0

3.3. Earthwork and Site Preparation

The surface of the embankment underwent various preparations to ensure its suitability for the Geo-membrane installation. These preparations involved leveling, dressing, and compacting the surface to eliminate any angular or sharp fragments, foreign matter, organic matter, stones, and pebbles that could potentially cause pinholes or punctures in the Geo-membrane. Additionally, great care was taken to remove any decomposable organic matter or vegetation from the site to prevent gas generation and upliftment beneath the Geo-membrane. Weeds, roots, vegetation, deep-seated live roots, pebbles, and stones were diligently cleared from the embankment surface. Prior to installation, the site was thoroughly inspected for the presence of crab and rodent burrows. Any burrows found were emptied of crabs and rodents and disposed of at a safe distance. The empty burrows and potholes on the bed and slope were filled with soil, which was then compacted manually and using suitable equipment to achieve at least 90 percent relative compaction. This meticulous compaction and levelling of the bed and slopes provided optimal support for the Geo-membrane.

3.4. Anchor Trench and Installation of HDPE Geo-membrane

An anchor trench was excavated parallel to the slope, at a distance of 80 to 100 cm from both the top edge and bottom edge of the slope. The trench had a depth of 24 inches and a width of approximately 12 inches, in accordance with the design drawing specifications. Special care was taken during trench construction to prevent direct contact between construction equipment and the Geo-membrane. To ensure smooth installation of the Geo- membrane, rounded corners were created in the trench to avoid sharp bends that could damage the material. Once the installation of the Geo-membrane was completed, the anchor trench was promptly backfilled.

Before commencing the Geo-membrane installation, a quality assurance certificate was obtained to ensure proper site preparation. All installers wore non-damaging footwear, and strict measures were in place to prohibit smoking or any actions that could potentially harm the Geo-membrane. In the event of any damages, appropriate repair procedures were followed. During the placement of Geo-membrane panels, efforts were made to minimize handling and provide sufficient slack to accommodate any shrinkage. The work area was designated as a "No Smoking" zone, and field assistants wore flat rubber-soled footwear to prevent damage to the embankment surface.

Great care was taken during the unrolling of Geo-membrane panels to prevent scratches or creases. The panels were properly positioned on the bed and slopes, ensuring a minimum overlap of 100 mm. At corners, the panels were carefully matched and aligned with the embankment slope's shape, typically an inverted triangle. Adjacent liner panels were joined together on the slope. To minimize the risk of wind flow under the panels, counterweights in the form of filled sandbags were placed along the panel edges and the toe of the embankment.

The interface of Geo-membrane seams was kept clean and free from dust to ensure proper sealing. Installation was not carried out during rainy conditions, excessive moisture, areas with standing water, or in the presence of high winds, fog, or dew. Any areas of the panel that suffered significant damage were marked and repaired accordingly. Geo-membrane deployment was halted during excessively high temperatures, as it could compromise the quality of the seams.

4. Results and Discussion

In order to address the identified problem of steady state seepage (referred to as the "steady state seepage problem" hereafter), an advanced solution was necessary. Various solutions were proposed by experts, such as adding an additional counter berm with a new rock toe to increase the factor of safety and stabilize the section, thus bringing the phreatic line within the sections. However, the challenging site conditions and the need for quality control and proper field compaction posed significant challenges. Given the severity and urgency of the problem, a decision was made to obstruct the water flow into the embankments and provide additional weight on the upstream slope to enhance the safety of the vulnerable downstream portions.

To achieve this, it was determined that a double-textured HDPE Geo-membrane with a thickness of 1 mm, along with suitable-sized gabions on the upstream side, would be utilized. Previously, designs and numerical solutions proposed homogenous embankments and too poorly compacted with no drainage arrangements, which led to anisotropic conditions within the section and water seeping out cutting the phreatic line. [34-37] The specifications for the 1 mm thick HDPE Geo-membrane were promptly drafted considering crucial parameters such as hydraulic resistance and puncture strength, particularly when placing gabions over it. Given the various standards for geo-synthetics, such as BS, ISO, ASTM, etc., it was imperative to base the guidelines on Indian Standards to develop the specifications.

Regarding the gabions, high-quality stones with a density of approximately 2 t/m^3 were selected and used within a 30 cm thick gabion cage coated with galvanized zinc. These gabions served as additional weight on the upstream side of the embankment. GeoStudio Numerical Modelling: An endeavor was undertaken to simulate the actual field conditions and scientifically validate the effectiveness of the implemented solution. The following arguments support the model's validity. It is crucial to acknowledge that the same problem persisted across the surrounding embankments, so a representative typical section was selected to adequately portray the issues.

In Case 1, the model addressed a steady state seepage condition as observed on the field, depicted in Figure 3. This initial case aimed to replicate the precise field conditions, including the absence of a rock toe and water rising to the Full reservoir level during monsoon. The site situation was modelled using the seep/w analysis. The model considered saturated soil conditions, which resulted in reduced cohesion, weakened strength, and a corresponding decrease in the factor of safety for the downstream slope. The Mohr-Coulomb failure model was employed, taking into account the characteristics of the underlying foundation layers. To simplify the modeling process, an anisotropic angle indicating the poor compaction control in the original construction work of 0 degrees was assumed, and the in-plane permeability coefficients in both directions were considered equal. As a normal steady state analysis was performed, the volumetric water content and compressibility were assumed to be negligible. The flow field was clearly observed.

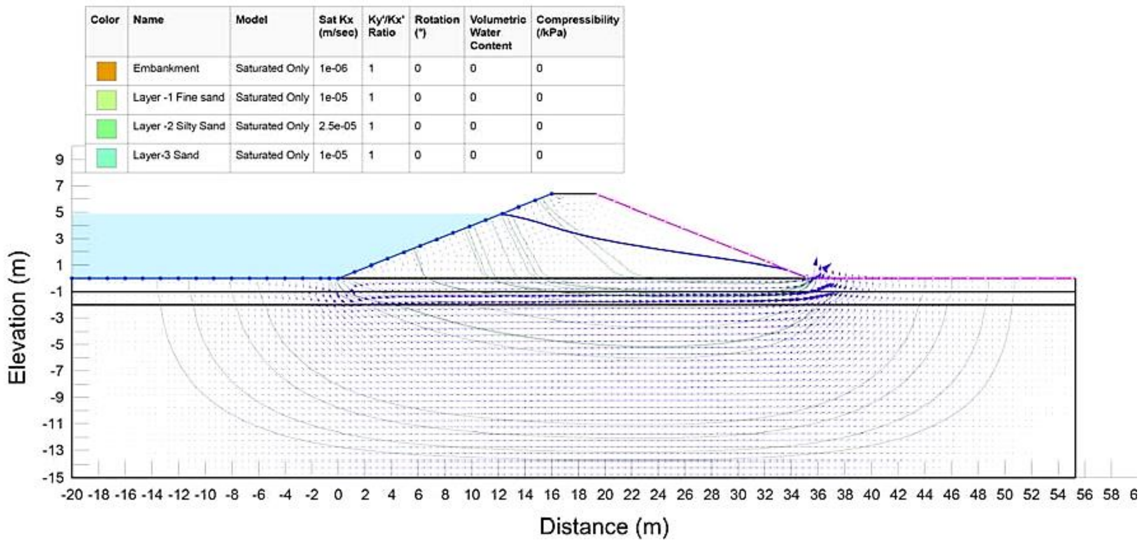


Figure 3. Steady state seepage condition simulating the exact field conditions

In Case 2, a combined steady state condition analysis and the slope stability(slope/w and seep/w) for assessing the local factor of safety of the downstream slope was simulated, as depicted in Figure 4. Model Geometry,soil properties ,founding soil layers and their properties and the hydraulic parameters used in the seep/w analysis of Case 1 were considered Following the development of the geometric model and analysis from the first case, a limit equilibrium analysis (slope/w) using the Modified Bishop's method was conducted, incorporating the same assumptions as in the previous case. Case 2 aimed to evaluate the potential possibility for local instability during seepage and assess the factor of safety of the downstream slope as the stability of the downstream slope is the most critical. The factor of safety was found to be marginally safe. The case 2 clearly elicited a feasibility for a local downstream slope failure surface passing through the foundation soil. Additionally, this minimum factor of safety elicited the chance of progressing global deep seated failure. Henceforth the potential of evaluation for deep seated failure became an obvious case, which was performed in the subsequent case.

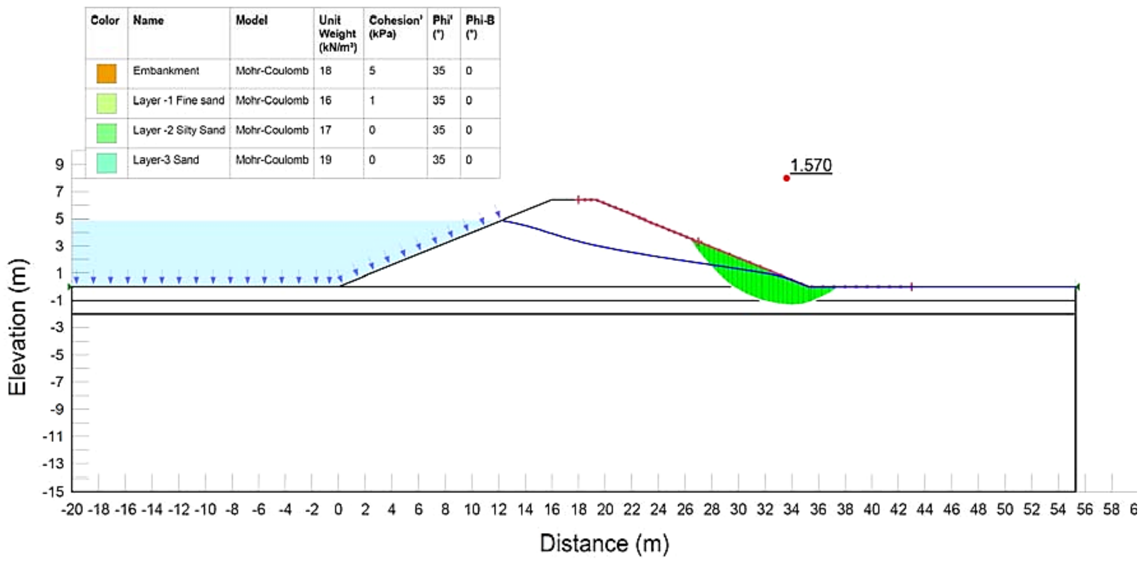
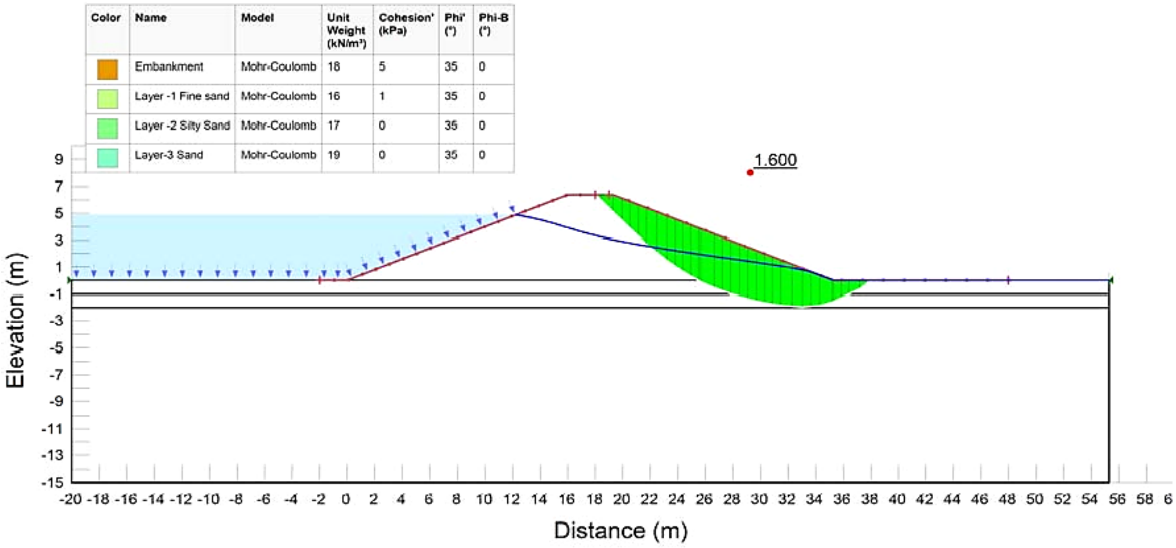


Figure 4. Steady state condition with local factor of safety of downstream slope with analysis of the first case

In Case 3, a combined steady state condition analysis and the slope stability(slope/w and seep/w) for assessing the global deep seated factor of safety of the downstream slope was simulated, as depicted in Figure 5. Model Geometry, soil properties, founding soil layers and their properties and the hydraulic parameters used in the seep/w analysis of Case 1 were considered Following the development of the geometric model and analysis from the first case, a limit equilibrium analysis (slope/w) using the Modified Bishop's method was conducted a global deep-seated factor of safety under steady state seepage conditions was modeled, as shown in Figure 5. Following the assessment of potential local instability, the Modified Bishop's method was used to determine the deep-seated factor of safety. This confirmed a risk of deep-seated downstream slope instability progressing from local instability. So the downstream slope will first become locally unstable and thereby the failure surface advancing throughout the downstream slope.



Note: It should be carefully noted that all the three cases described above are modelled considering original site situations. Perhaps the usage of berm, gabions and the Geo-membrane is not modelled.

Figure 5. Global deep-seated factor of safety under the steady state seepage condition under a potential local instability

In Case 4, a steady state seepage scenario was modeled, incorporating the Geo-membrane and Gabion, as presented in Figure 6. A seep/w analysis was performed after incorporating the Geo-membrane as a soil layer with zero permeability and utilizing gabions according to the specified specifications. The analysis clearly demonstrated an increased flow towards the foundation strata and not significantly through the downstream slope as compared to Case 1. The GeoStudio model provided a clear representation of the numerical simulations mentioned above

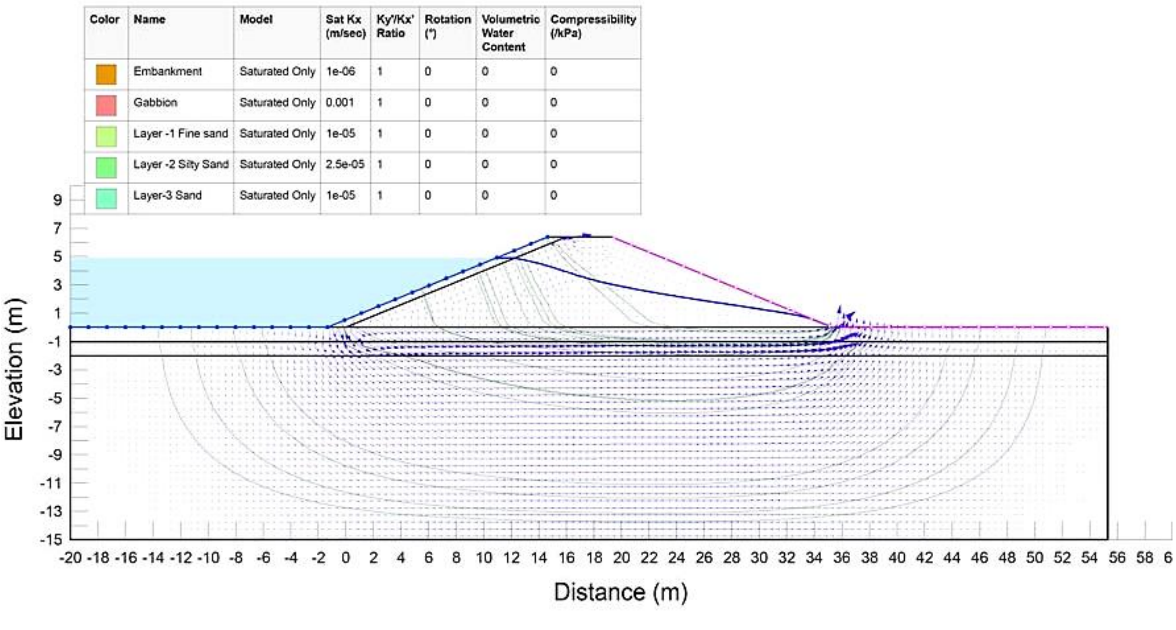


Figure 6. Steady state seepage along with Geo-membrane and the Gabion

In Case 5, model geometry, soil properties both in the foundation and the slope remained the same as described in earlier cases except incorporating the placement of the Geo-membrane and Gabions, as shown in Figure 7 a steady state condition with the local factor of safety of the downstream slope was modeled, incorporating. Modeling using seep/w and slope/w analysis indicated a marginal increase in the local factor of safety of the downstream slope. Similarly, the possibility of the progressing global deep seated failure was mandated and hence the corresponding factor of global safety was performed in the subsequent case.

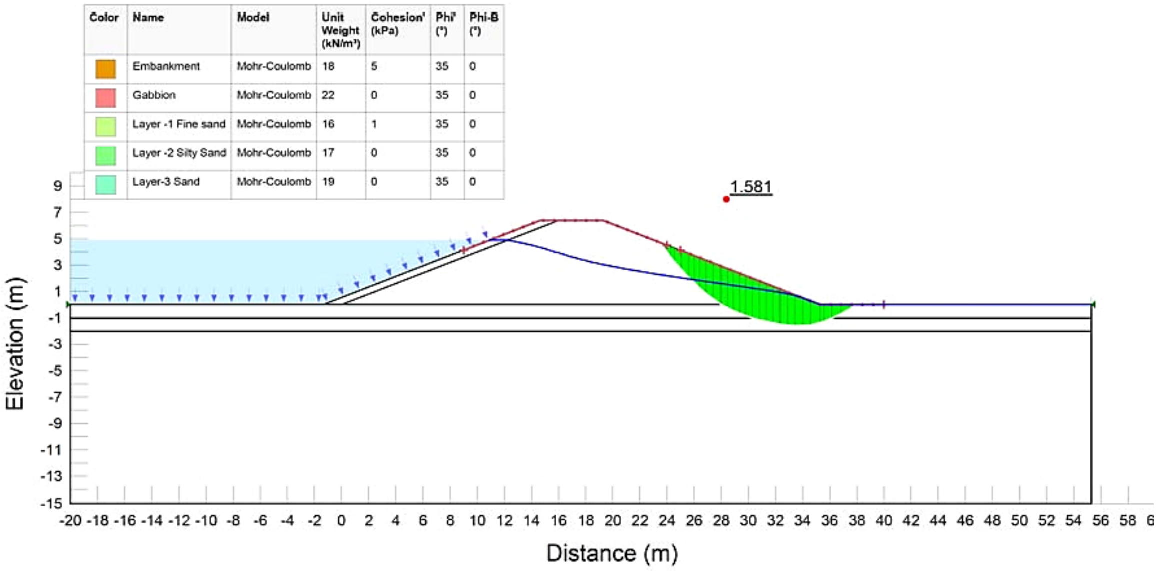


Figure 7. Steady state condition with local factor of safety of downstream slope when Geo-membrane and Gabions are placed

In Case 6, a global deep-seated factor of safety under steady state seepage conditions, following the placement of the membrane and Gabions, was modeled, as presented in Figure 8. After assessing the potential local instability, a significant increase in the deep-seated factor of safety was observed. The analysis employed the same methodology (Bishop's Method). There is clear cut increase in the minimum factor of safety by installing the Geomembrane and the gabions globally.

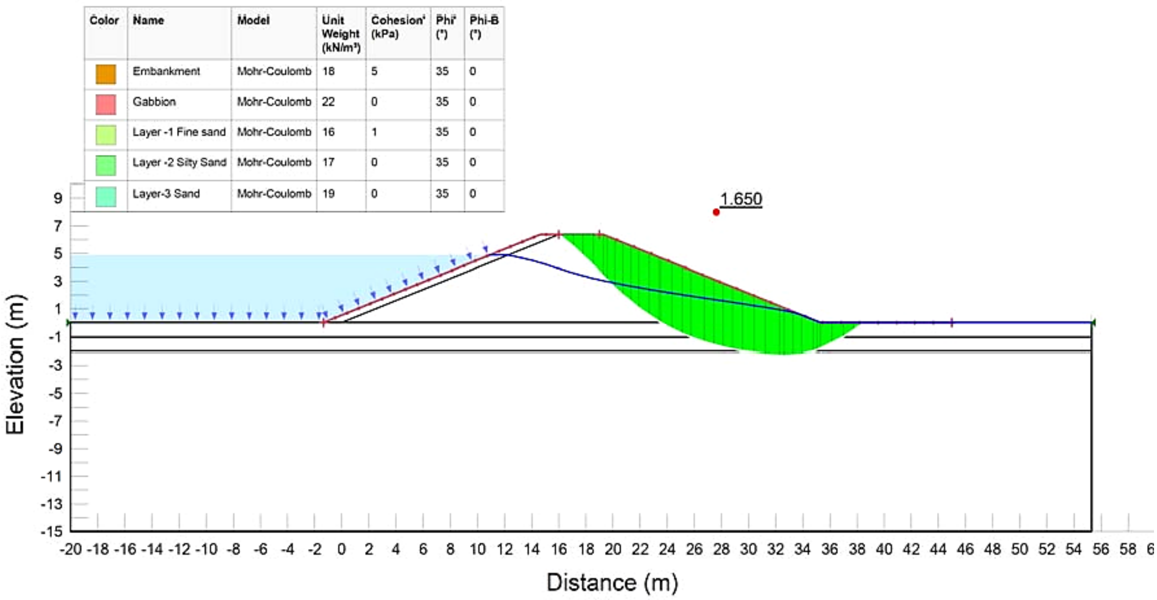


Figure 8. Global deep-seated factor of safety under the steady state seepage condition after membrane and Gabions placed

In Case 7, a steady state seepage scenario was modeled, incorporating the Geo-membrane, Gabions, and a Rock Toe, as illustrated in Figure 9. The main objective here was to increase the drain ability and increasing the factor of safety a seep/w analysis was performed after incorporating the Geo-membrane as an equivalent soil layer with zero permeability and utilizing gabions according to the specified specifications, along with the addition of a rock toe. The GeoStudio model clearly demonstrated that a significant portion of the flow was redirected towards the Foundation strata. The results clearly depicted an increased downward percolation so as to recharge the groundwater table.

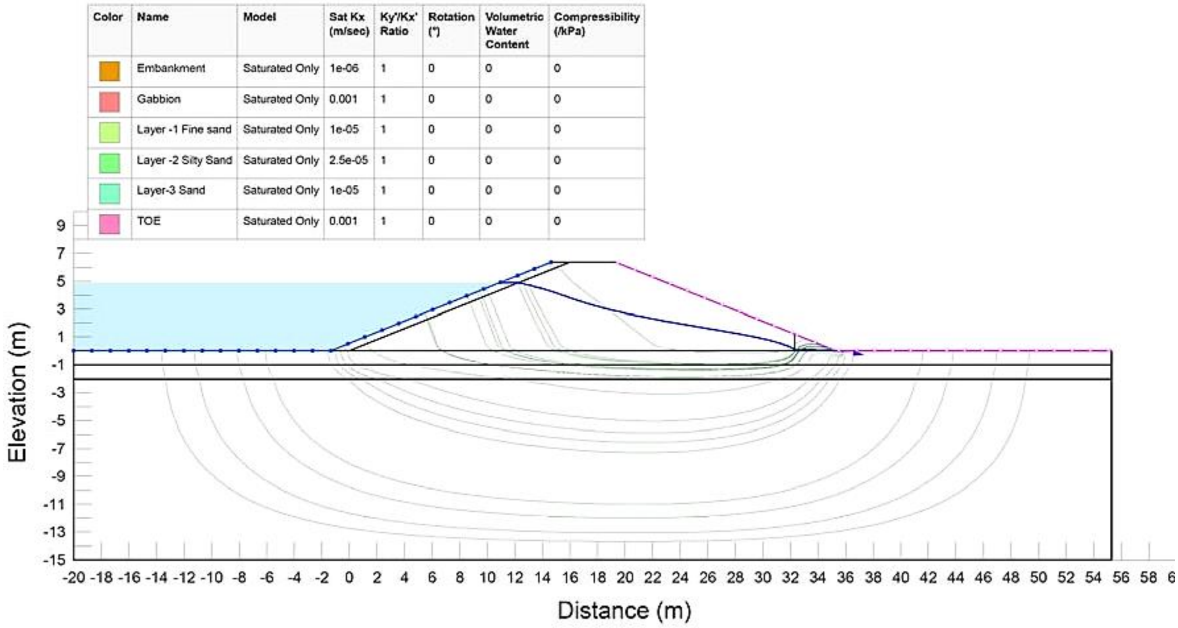


Figure 9. Steady state seepage along with Geo-membrane, Gabion and Rock Toe

In Case 8, a steady state condition with the local factor of safety of the downstream slope was modeled, incorporating the placement of the Geo-membrane, Gabions, and Rock Toe, as shown in Figure 10. Similar modeling using slope/w and seep/w analysis revealed a substantial increase in the local factor of safety of the downstream slope. Rest every aspect of model Geometry and soil properties in the embankment and the foundation remained the same.

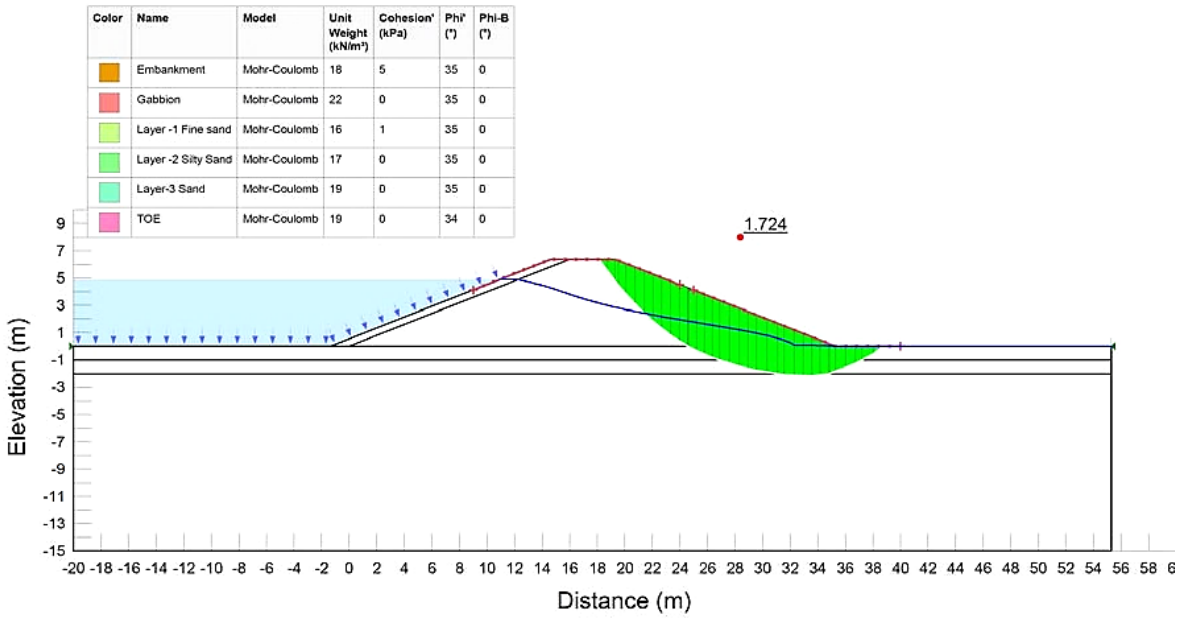


Figure 10. Steady state condition with local factor of safety of downstream slope when Geo-membrane, Gabions and Rock Toe are placed

In Case 9, a global deep-seated factor of safety under steady state seepage conditions, following the placement of the membrane, Gabions, and Rock Toe, was modeled, as presented in Figure 11. After assessing the potential local instability, a significant increase in the deep-seated factor of safety was observed. The analysis employed the same methodology (Bishop's Method).

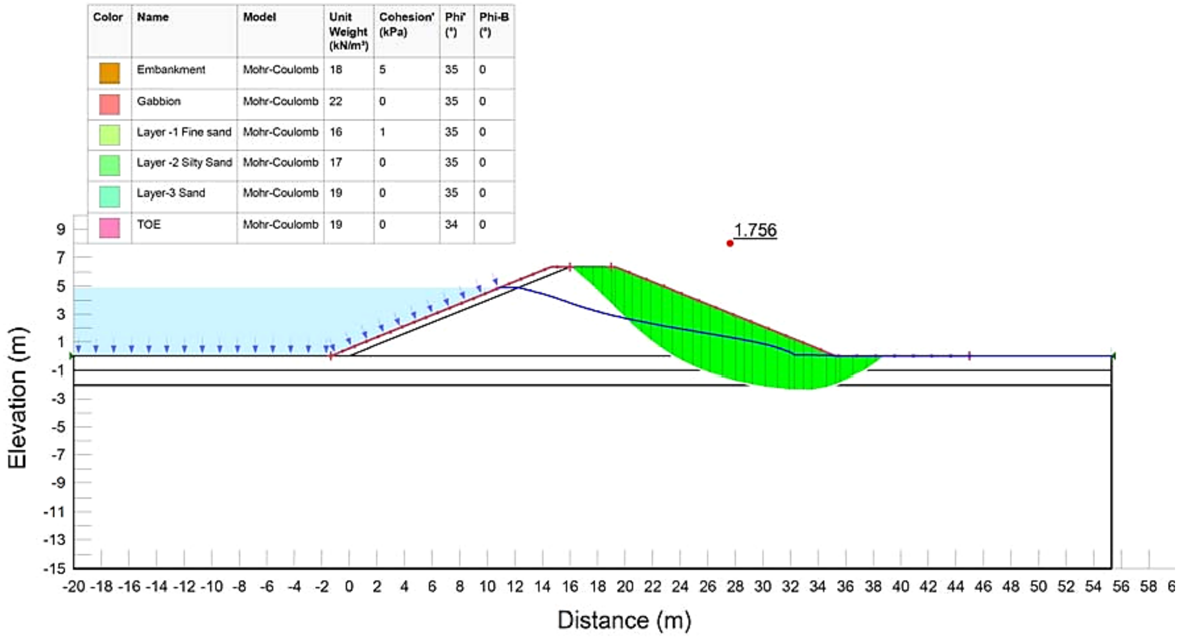


Figure 11. Global deep-seated factor of safety under the steady state seepage condition after membrane Gabions and Rock Toe placed

Finally, a summary of the model cases and the achieved factor of safety values are presented in Table 3.

Table 3. Summary of the model cases

Case	Figure	Description	FOS
1	2	Exact field conditions	Steady state seepage
2	3	Local FOS Analysis of the 1st case	1.570
3	4	Global deep-seated FOS Analysis of the 1st case	1.600
4	5	Geo-membrane and Gabion	Steady state seepage
5	6	Local FOS Analysis of the 2nd case	1.581
6	7	Global deep-seated FOS Analysis of the 2nd case	1.650
7	8	Geo-membrane , Gabion and Rock Toe	Steady state seepage
8	9	Local FOS Analysis of the 3rd case	1.724
9	10	Global deep-seated FOS Analysis of the 3rd case	1.756

5. Conclusions

This research aims to investigate the improvement in the downstream slope of Pashwada Dam using two alternative techniques to reduce the seepage through the dam. The following are the concluding remarks drawn from the investigation:

- Previously, designs and numerical solutions proposed homogenous embankments that were too poorly compacted with no drainage arrangements, which led to anisotropic conditions within the section and water seeping out, cutting the phreatic line.
- The first is to cover the upstream slope with HDPE geo-membrane stabilized by gabions, and the second is the same as the first in addition to rock toe in the downstream.
- Both techniques were studied using LS-FEM modeling, where the seepage was analyzed using the FEM model and the calculated pore water pressure values were used to study the stability of the downstream slope using the limit state method (modified Bishop's method).
- The study results showed that using the HDPE geo-membrane alone slightly enhanced the downstream slope stability (by 3%); on the other hand, using the HDPE geo-membrane in combination with rock toe significantly enhanced the stability (by 10%).

- This extra enhancement is achieved due to the double action of reducing the seepage due to the zero permeability of the HDPE geo-membrane and reducing the pore water pressure at the toe of the downstream slope due to the high permeability of the rock toe (decrease the input discharge to the embankment and increase the output discharge from the embankment).
- Generally, future research works are expected to study the application of other dam enhancement materials and also deploy different numerical techniques, especially those belonging to mesh-free techniques like smoothed particle hydrodynamics (SPH).

6. Declarations

6.1. Author Contributions

Conceptualization, K.C.O.; methodology, A.M.E.; formal analysis, A.N.; investigation, N.G.R.; data curation, J.A.B.; writing—review and editing, K.C.O., A.N., N.G.R., J.A.B., S.H., and A.M.E.; supervision, S.H. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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