Probabilistic Analysis of the Slope of Nai Gaj Dam During Rainfall Infiltration

Sadaf Qasim[1*], Halima Bano[2], Sadia Moin[1], Sharafat Ali[3], Ejaz ul Haq[1], Hafiz Farhan[1], Muhammad Maaz[1], Muhammad Hamza[1], Furqan Khan[4], Faryal Sikander[4]

[1]Department of Civil Engineering, NED University of Engineering & Technology, Karachi, Pakistan

[2]Department of Civil Engineering, Dawood University of Engineering & Technology, Karachi, Pakistan

[3]College of Civil Engineering and Architecture, Henan University of Technology, Henan, China

[4]Department of Architecture & Planning, Dawood University of Engineering & Technology, Karachi, Pakistan

Abstract

This paper *employs a probabilistic analysis method to demonstrate the durability of earth-fill Dam slopes under stress. The Nai Gaj Dam is located around 65 kilometers in the northwestern part of the Dadu district of Sindh, Pakistan. This study calculates and simulates the seepage and rainwater infiltration through the main Dam's embankment for various scenarios, including a full and approximately halfway between the maximum and minimum reservoir levels.*

Using Rocscience's Slide 2D slop 6.0 software, deterministic and probabilistic analysis was carried out. Input data utilized to calculate the Dam slope stability unknown seepage included Dam design parameters and geometry information. Nai Gaj Dam seepage behavior is demonstrated by equipotential lines, streamlines, and velocity vectors in net flow. The outcomes display the exit gradient, maximum seepage, and seepage flux. The findings indicate that the flow rate at the highest reservoir level is 60.47 cubic meters per day. Probabilistic analysis is also used to examine the Dam's overall stability side slope at maximum and mid-reservoir levels. It shows that while the reliability index is 3.66 at mid-level and the likelihood of failure is 0%, it is -4.26 at the whole reservoir level and has a 97% probability of failure.

Keywords: *Stability of Dam, Bishop Method, Janbu Method, Fellenius Method, Spencer Method, Seepage Analysis.*

Introduction

Pakistan is a predominantly agricultural country. Water irrigation is the mainstay of Pakistani agriculture. Many Dams have been built, and many more are scheduled in the future. Embankment Dams are substantial, expensive works of civil engineering that provide vital water control infrastructure. Dams are physical obstructions that limit the free flow of water. They build reservoirs that can control floods, produce power, and supply water for human usage in things like agriculture, industry, and municipal needs. Despite being beneficial to humanity, the Dams have negative repercussions on populations downstream, including implications on the security of people, the environment, and property. Accidents or breaches at dams could cause uncontrolled water releases, which would cause tremendous damage and fatalities [2]. Due to the restricted permeability of soils, excessive pore pressure may progressively increase throughout the raising and filling of the Dam. This elevated pore pressure may result in dam or slope failure. Nearly 50% of embankment Dam failures are assumed to be caused by pore pressure stress, seepage, internal erosion, and severe deformations [3]. Dam stability against slope instability is critical for designing and operating all water shortage conditions. According to an examination of historical Dam failures, seepage-induced internal erosion was responsible for roughly half of all embankment Dam collapses. Detailed seepage evaluation through and beneath the Dam body should be a part of any Dam component's design, construction, and maintenance. Most Dam geotechnical studies included seepage and stability analyses that considered pore pressure fluctuations in unsaturated ground conditions.

Developing nations currently do not take into account the effect of rainfall infiltration on the stability of earth dam slopes when assessing the safety of embankment dams. However, due to the porous nature of the Dam slope, particularly the downstream Dam slope, rainfall infiltration may have a considerable impact on the stability of the Dam slope and the strength of the Dam soil. Probabilistic techniques are a reasonable way to include uncertainties in Dam safety studies since the strength properties of Dam soils are diverse and unpredictable, and because the traditional safety factor cannot directly address these uncertainties. Slope stability analysis has long used risk and probabilistic approaches [4].

The Dadu District in Sindh Province of Pakistan, approximately 65 kilometers (40 miles) northwest of Dadu City, is where the Nai Gaj Dam is being built. It is an embankment Dam constructed on the Gaj River in the valley area at the edge of the Kirthar Mountains range. Its power plant will be fully operational and have an installed capacity of 4.2 MW. Additionally, the Nai Gaj Dam would provide 50 cusecs of water to Lake Manchar to lessen pollution. The Nai Gaj Dam is an Earth Core Rockfill Dam, 194 feet (59 meters) in height, with a live storage capacity of 0.16 MAF, a gross storage capacity of 0.30 MAF, and a dead storage capacity of 0.140 MAF. Its spillway capability is 253000 cusecs, and the Dam project is about 51 percent finished physically. Despite all the advantages of a Dam, structural failure can result in significant losses by generating unplanned floods in the downstream area. Dam break analysis is essential to forecast flooding levels. It is vital to research the load-bearing capacity of local soils and their impacts on the stability of Dams throughout their service conditions to maintain the protection of existing and future Dams in Pakistan. In Pakistan, there are very few published reports on Dam stability issues. Rainfall or water infiltration causes seepage failures by changing the amount of pore water pressure. An analyst must know about leakage, its solutions, and the protective methods for monitoring it. The bulk of all built Dams is filled with rock or dirt. Because of their large population and the significant losses that their collapses can cause, engineers must analyze the safety of embankment Dams. However, because embankment Dams are made of natural materials (soils, sands, or rocks), there is a significant degree of uncertainty around their construction, making it challenging to assess their safety. A reliable approach or a sensitivity method can be used to quantify the effects of the soil variability on the Dam safety condition using probabilistic analysis, which is an efficient solution. A probabilistic analysis can also yield data complementary to a conventional deterministic evaluation, such as the failure probability (Pf), design point, model response statistics (such as mean and variance), and reliability index. More data will help planners better understand the Dam's operation and enable them to make more thoughtful choices. Therefore, it is essential to use probabilistic calculations to account for soil variability and provide additional information when evaluating the safety of embankment Dams [5]. Embankment Dams are being built to accommodate the rising need for electricity and water. To address Pakistan's challenges with water and electricity shortages, several embankment dams are being constructed and will be erected in the future. Utilizing a suitable constitutive model for a specific soil and loading conditions would depend on the availability of an acceptable form of modern laboratory testing to assure the safety of embankment Dams and stability [6, 7]. Depending on the region's geology, the budget allotted for the geotechnical analysis of embankment Dams is typically between 1 and 3 percent of the entire cost [8]. These days, it is possible to estimate the settlement of embankment dams using finite element models. The Plaxis 2D limited element program, which has a library of numerous constitutive models that can be applied to diverse soils, is one such limited element program used in geotechnical engineering. In Plaxis 2D, a number of sophisticated constitutive models are implemented beginning with the linear elastic model [9]. The objective here is to perform a deterministic analysis of the Nai Gaj Dam embankment using the limit equilibrium method. Furthermore, it serves as a probabilistic analysis of the Nai Gaj Dam from rainfall infiltration. This study also focuses on doing a comparative analysis of both the methods approaches earlier.

Literature Review

A slant disappointment happens when the world's self-retain ability is undermined by precipitation, making the incline break down unexpectedly. Slant solidness is one of the most basic and one of the most intricate geotechnical issues. Due to the various vulnerabilities engaged with the interaction, it is especially challenging to decide on incline strength. Probabilistic methodologies are utilized related to the unwavering quality of dealing with represent these vulnerabilities. On Earth, Dams' disappointment might happen for various reasons, for example, primary flimsiness conditions, water-driven conditions, leakage through the Dam body, and quick drawdown. Ensuring security for the Dam's incline steadiness under various tasks is essential to discover the Dam's general well-being. Worked from locally available materials, a good Dam should be steady under all working and stacking circumstances, sufficiently waterproof to oversee drainage, and have adequate outlet attempts to forestall Dam overtopping. Dams are constructed for specific purposes, such as water storage for residential and agricultural use, flood control, recreation, fishing, and hydroelectric power generation. Dam design and construction must strictly follow safety standards and specifications. Under all flood and drought conditions, the Dam's stability against slope failure is critical for its construction and operation. By classifying them into three groups—seepage, slope stability, and internal erosion [10]. The Dams can fail for various reasons, just like other engineering projects, including poor designs, shoddy construction, and lack of maintenance. Regarding failures, the Dams are classified by [11] as:

1) Overturning failure accounts for 40% of all failures.

(2) 30 percent of seepage fails

(3) Structural flaws account for 30% of all structural collapse

Effect of Rainfall Infiltration on Earth Dam

The stability of the Dam slope is significantly impacted by rainfall infiltration. Due to the ability of soil to store water and the time-dependent changes in environmental conditions, such as rainfall and rising water tables, water flow and moisture content in undrained conditions can vary geographically and over time. Rain infiltration may significantly impact the strength of the soil surrounding the Dam and the stability of the Dam's slope. A crucial technique for assessing the stability of Dam slopes and the susceptibility of Dams to seepage failure is infiltration analysis [12]. The safety of Dams is affected gradually by rainfall. The amount, consistency, and rainfall duration make the structure unsafe/unstable. As the maximum intensity, length, and total precipitation of the downpour increase, the likelihood of Dam instability also increases [13]. One of the most frequent causes of earth Dam failure is internal erosion. It's possible that there isn't even a hint of evidence to suggest that it's happening. A Dam may burst in hours after signs of internal deterioration become apparent. When water is blocked behind a Dam, internal erosion may start immediately or may take years to develop. Internal erosion failures are frequently associated with Dam "penetration levels," such as discharge of underground pipes in the embankment, rodent activity, and concrete spillways that cross the embankment [14]. The flow, liquid properties, hydraulic gradient, and soil media all impact how much water seeps through a porous medium. Approximately 30% of all earth Dam failures result from seepage pipes. Many strategies have been developed to address seepage issues. These procedures fall within analytical, experimental, or numerical categories. Groundwater flows toward decreasing potential energy because of pressure and elevation differences. One common way to quantify this potential energy is to use the total head, which is just the sum of the pressure and elevation heads. The volume flow rate per unit area is directly proportional to the head change rate, according to the differential form of Darcy's Law [15].

Methodology

The procedures followed to conduct the probabilistic and deterministic study of Nai Gaj Dam are outlined in this section. Various research publications on Dam embankment slope failure in Pakistan were reviewed to gather accurate data for modeling. Slide software is used for the analysis. For Dam slope analysis, Nai Gaj Dam is selected as the study area. The selection of the Dam for analysis needs the data of embankment (material) like clay, sandy silt, etc. We have gone through many research papers to analyze the Dam of Pakistan. The most suitable Dam we found in the sense of data availability was Nai Gaj Dam, Dadu, Sindh, Pakistan.

Data Collection

Embankment Soil Properties of Nai Gaj Dam

Embankments are constructed of soil materials but may include aggregate, rock, or crushed paving material. Sand gravel, random fill, central impervious clay core, sand filter, coarse filter, and drainage blanket are the materials zones of the Nai Gaj Dam. The Dam's foundation is primarily built of sandstone. The highest design water level for this embankment Dam is 56.6m. It is 59m high, 1137m long, and has a maximum allowable water level of 56.6m.

Table 1: Embankment Soil Properties *of* Nai Gaj Dam [3]

Material Type	Saturated Unit Weight (kN/m3)	Cohesion (kN/m2)	Frictional Angle (deg)	Modulus of Elasticity (Kn/m2)	Permeability (m/day)
Clay	18.85	9.57	30	50000	0.000263
Sandy Gravel	21.5	0	37	50000	86.4
Random Fill	18.85	0	34	50000	0.0263
Washed Gravel	21.5	0	37	45000	864
D/s Slope protection	19.5	0	34	40000	8640
Riprap	19.5	0	34	40000	8640
Sand Filter	18.85	0	36	40220	26.33
Drainage Blanket	21.5	0	37	45000	864

Data Analysis

For information investigation, rock science slide 6.0 is utilized. A 2D slant solidness program called SLIDE decides the well-being component of disappointment surfaces that are round or noncircular on soil or rock inclines. SLIDE is staggeringly simple to use while considering the quick and basic creation and investigation of confounded models. There are many displaying choices for outer burdens, groundwater, and support. SLIDE uses vertical cut limit balance strategies to research the steadiness of slip surfaces. Individual slip surfaces, search methodologies, and different techniques can be utilized to decide the primary slip surface for a given incline. In this venture, simply the decisions demonstrated underneath are utilized. In the deterministic technique, slope/w uses the Ordinary, Bishop, M.P, and Janbu approaches. It provides us with the slope's safety factor.

Probabilistic (Non-Deterministic) Analysis

It's also known as the non-deterministic approach. It provides us with the failure probability, the reliability index, and the safety factor. The outcomes of this method provide a level of reliability to reduce the likelihood of slope collapse. It is a fact that there is no relation between factors of safety and reliability index as both are unrelated, but reliability and the likelihood of failure governs.

Generally, probabilistic analysis needs thousands of trials to conquer uncertainties; in this regard technique of Monte Carlo simulation must be driven.

Monte Carlo Simulation

It's a computer-assisted mathematics method. Randomly create value for uncertain variables to mimic a model. Using random variables, a large number of iterations are used to approximate the probability of specific outcomes. Random variables are created according to calculated fundamental statistical factors like mean, variance coefficient, and distribution type. A limit state function "G" is formed by combining the generic random variables (based on the already determined limit state function).

Seepage Analysis

In transient situations, the water reservoir's behavior is mostly to blame for how the equilibrium state varies over time (variation of the water reservoir level). These circumstances lead to variations in pore water pressures (PWP), which impact the equilibrium state. Deterministic research assumes that the safety factor (F.S.) will alter over time, reflecting changes in the water reservoir level. Similarly, the reliability index () and the probability of failure (Pf) in probabilistic research reflect the Dam's safety over time. However, it is uncertain when the minimal F.S., Pf, and occur. A discretized time step (tk, k = 0, 1..., K) must be used to execute the deterministic and probabilistic analysis. The pore water pressures at that time will impact the reliability analysis for limit equilibrium at any time tk. However, the PWPs at time tk are also random since some seepage parameters are. Because of how widely distributed PWPs are in space, describing unpredictability in them is challenging. Alternately, by doing random seepage studies starting at time zero, the right random PWPs at time tk can be discovered. This entails starting over from time zero and doing the entire random seepage analysis for the PWPs at time tk+1. It has a high computational cost when computing numerical solutions with several degrees of freedom. The reservoir's water level continually rises and falls under the Normal Operation Conditions (NOC) investigated here, attenuating substantial variations in PWPs that may be caused by highly high realizations of volumetric water content or hydraulic conductivity. A practical implication is that analyzing the entire seepage time history is not essential. Given the size of the finite element models used in the study and the length of the investigated Dam's life, this is very pertinent to the subject matter [16].

Fundamental Equations

The following differential equation examines seepage through the Dam's body at its foundation. The finite element method is employed in this study to describe the groundwater flow in a porous medium. Equations are derived using the mass conservation law as a foundation. In SEEP/W, the partial differential equation is utilized:

$$\frac{\partial}{\partial_x}\left(K_x\frac{\partial H}{\partial X}\right)+\frac{\partial}{\partial_y}\left(K_y\frac{\partial H}{\partial Y}\right)+Q=\frac{\partial Q}{\partial_t}\quad (1)$$

Where H denotes hydraulic head, Kx and Ky denote horizontal and vertical hydraulic conductivity, Q denotes discharge, and t denotes time-domain and volumetric water content.

The above equation represents the transient flow and is a two-dimensional, nonlinear, second order PDE. It is an extension of Darcy's Law:

$$v = -K \nabla H \quad (2)$$

where:

$$\nabla H = \begin{bmatrix} \frac{\partial H}{\partial x} \\ \frac{\partial H}{\partial y} \end{bmatrix} \quad (3)$$

Where v represents velocity, K represents the hydraulic conductivity of the soil medium, and ∇ H represents the hydraulic gradient. Equation (1) depends on time and tells that the flow enters an elemental volume minus the flow, leaving the elemental volume at a point equal to the volumetric water content.

$$\frac{\partial}{\partial_x}\left(K_x \frac{\partial H}{\partial_X}\right) + \frac{\partial}{\partial_y}\left(K_x \frac{\partial H}{\partial_Y}\right) + Q = 0 \quad (4)$$

Reliability Theory

It is already reported that reliability theory helps quantify the cumulative consequences of uncertainty [1, 17]. The main issue with the safety factor technique is that it cannot account for uncertainties, even for long-term slope stability; the exact value is used without regard for the level of calculation uncertainty. Peck proposed the observational technique to cope with uncertainties in this connection, although its applicability is limited to circumstances where designs may be changed [18,19]. Geotechnical engineers, like other disciplines, have created various ways to address uncertainty[17]. It is realized that. If uncertainties created by different routes are well understood and rigorously examined, the level of risks can be reduced. Among other methods, reliability analysis is regarded as the most effective instrument for overcoming uncertainties caused by various sources [20].

A reliability study seeks to quantify the likelihood that capacity surpasses demand. Because both demand (loading) and capacity (bearing capacity) are ambiguous. Figure 1 defines a straightforward reliability theory application. It is one of the critical components of reliability-based design. The reliability index () in reliability analysis represents the probability of failure (Pf). U.S. Army Corps of Engineers has already established the correlation between reliability theory and the probability of failure regarding performance level (Refer to Table 2).

According to the U.S. Army Corps of Engineers, it is preferable to compute reliability indices higher than the goal values before beginning any repair effort. The fundamental goal of the index is to provide a reliable estimate of the performance that will be delivered [21].

Table 2: Reliability Index and Failure Probability Correlation[21]

Performance Level	Reliability Index	Probability of Failure
High	5	0.0000003
Good	4	0.00003
Above Average	3	0.001
Below Average	2.5	0.006
Poor	2	0.023
Unsatisfactory	1.5	0.07
Hazardous	1	0.16

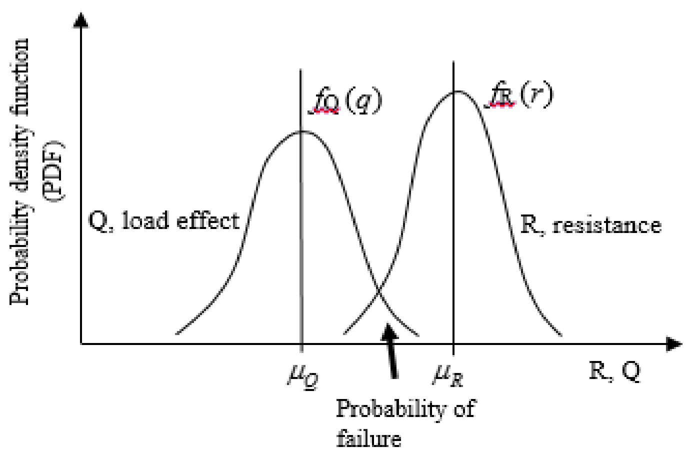

Figure 1: Joint Probability distribution [1]

Results & Discussion

To analyze the Nai Gaj Dam, "Rock Science Slide 6.0" software is used. The Dam's embankment is drawn in software using actual parameters from the literature review. Three analyses have been done: deterministic analysis, probabilistic analysis, and seepage analysis to obtain Factor of Safety (FOS), reliability index (R.I.), discharge flow rate, etc., using actual embankment material and rainfall infiltration data.

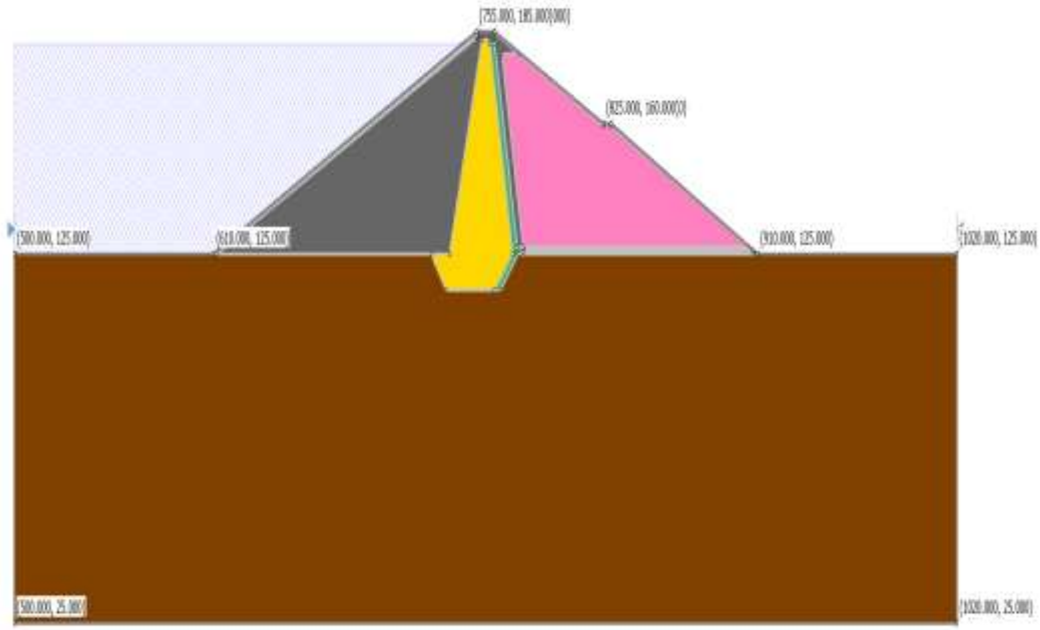

Figure2: Dam Embankment coordinates

Table 3: Material Properties

Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface	Phi b (deg)	Air Entry (kPa)
clay core		9.04	Mohr-Coulomb	9.57	30	None	0	0
sandy gravel		11.69	Mohr-Coulomb	0	37	None	0	0
Random fill		9.04	Mohr-Coulomb	0	34	None	0	0
Washed gravel		11.69	Mohr-Coulomb	0	37	None	0	0
D/s slope protection		9.69	Mohr-Coulomb	0	34	None	0	0
RipRap		9.69	Mohr-Coulomb	0	34	None	0	0
sand filter		9.04	Mohr-Coulomb	0	36	None	0	0
Drainage blanket		11.69	Mohr-Coulomb	0	37	None	0	0
sandy siltstone		10.59	Mohr-Coulomb	12	29	None	0	0

Hydraulic Properties from Software

Table 4: Hydraulic Properties

Material Name	Color	Model	KS (m/s)	K2/K1	K1 Angle (deg)	Soil Type
clay core		Simple	3.04e-009	1	0	Clay
sandy gravel		Simple	0.001	1	0	Sand
Random fill		Simple	3.04e-007	1	0	General
Washed gravel		Simple	0.01	1	0	General
D/s slope protection		Simple	0.1	1	0	General
RipRap		Simple	0.1	1	0	General
sand filter		Simple	0.000304	1	0	Sand
Drainage blanket		Simple	0.01	1	0	General
sandy siltstone		Simple	7.3e-009	1	0	Sand

Deterministic Analysis

Bishop, Janbu, and Fellenius are three alternative deterministic analytic techniques that yield the Factor of Safety.

By Bishop Method

FOS without water table: 1.632

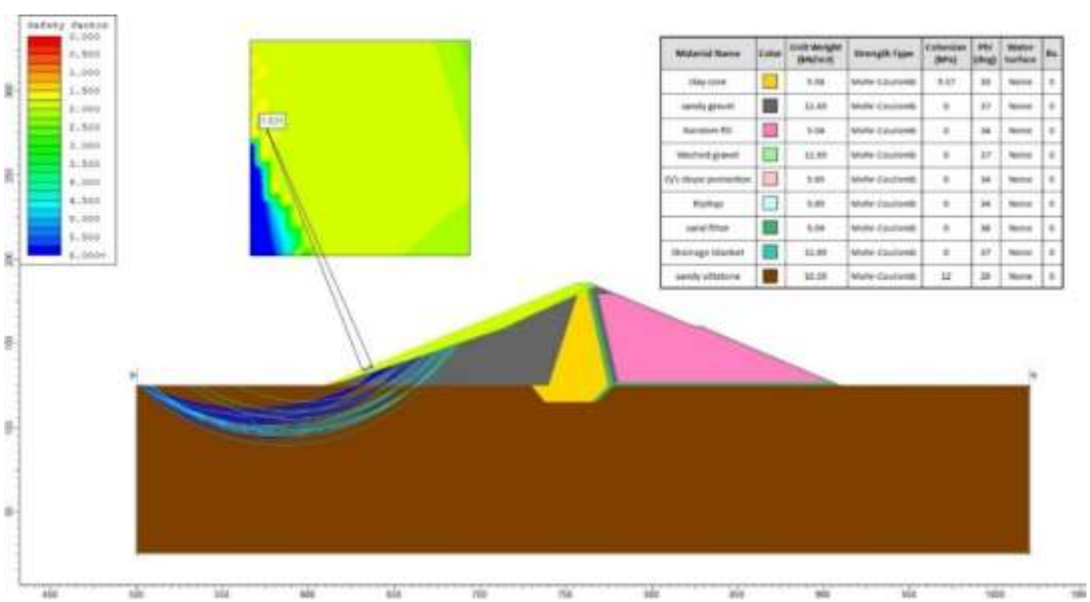

Figure 3: Deterministic Analysis W/O Water Table Bishop Method

FOS with water table: 0.652

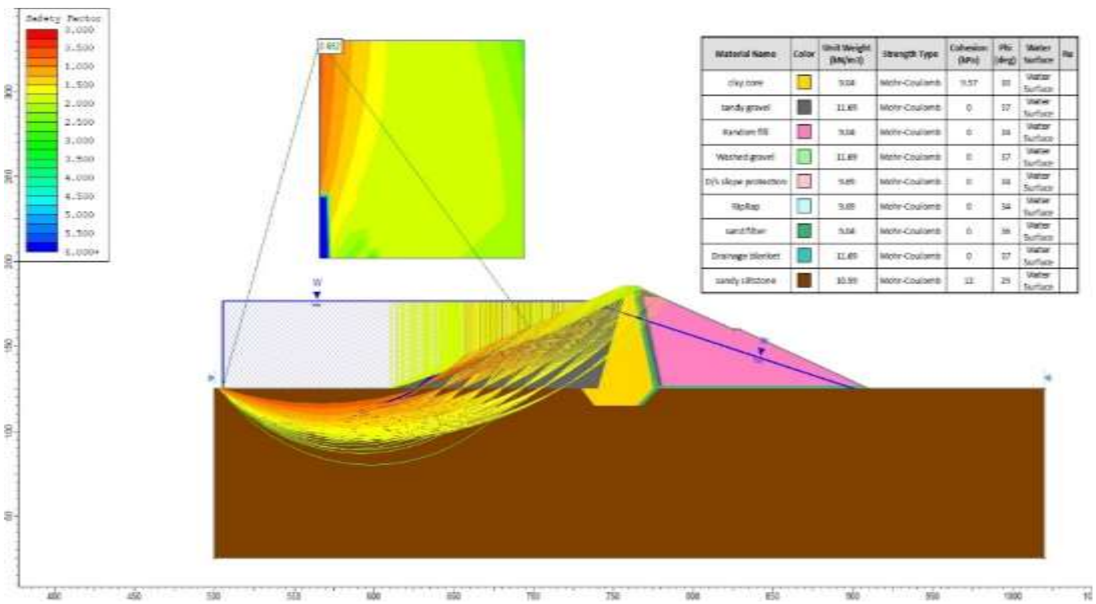

Figure 4: Deterministic Analysis with Water Table Bishop Method

By Janbu Method

FOS without water table: 1.633

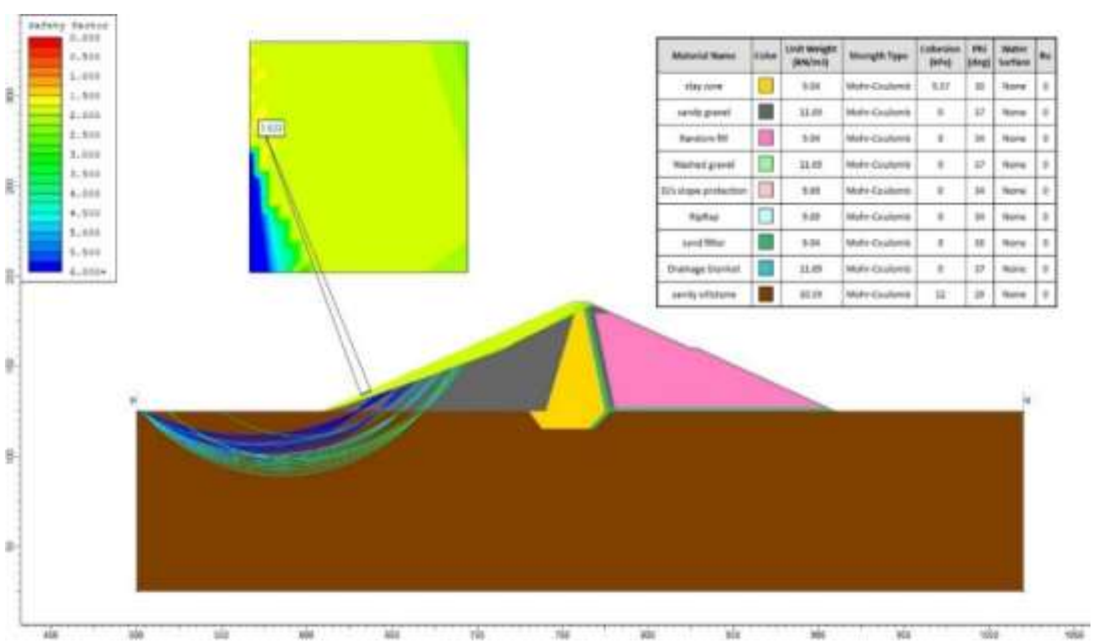

Figure 5: Deterministic Analysis W/O Water Table Janbu Method

FOS with water table: 0.593

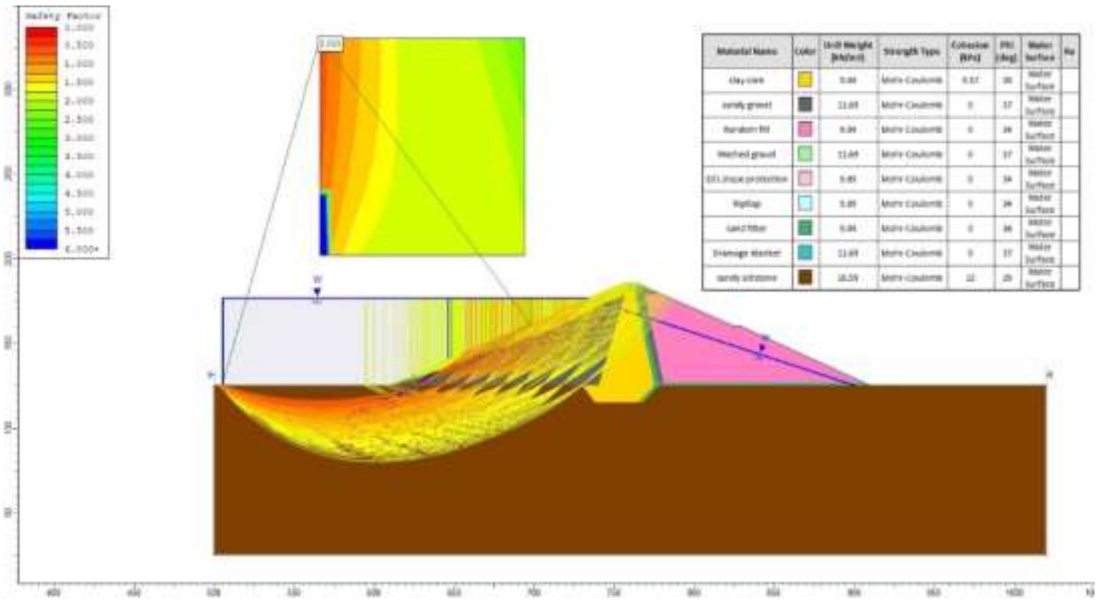

Figure 6: Deterministic Analysis with Water Table Janbu Method

By Fellenius Method

FOS without water table: 1.630

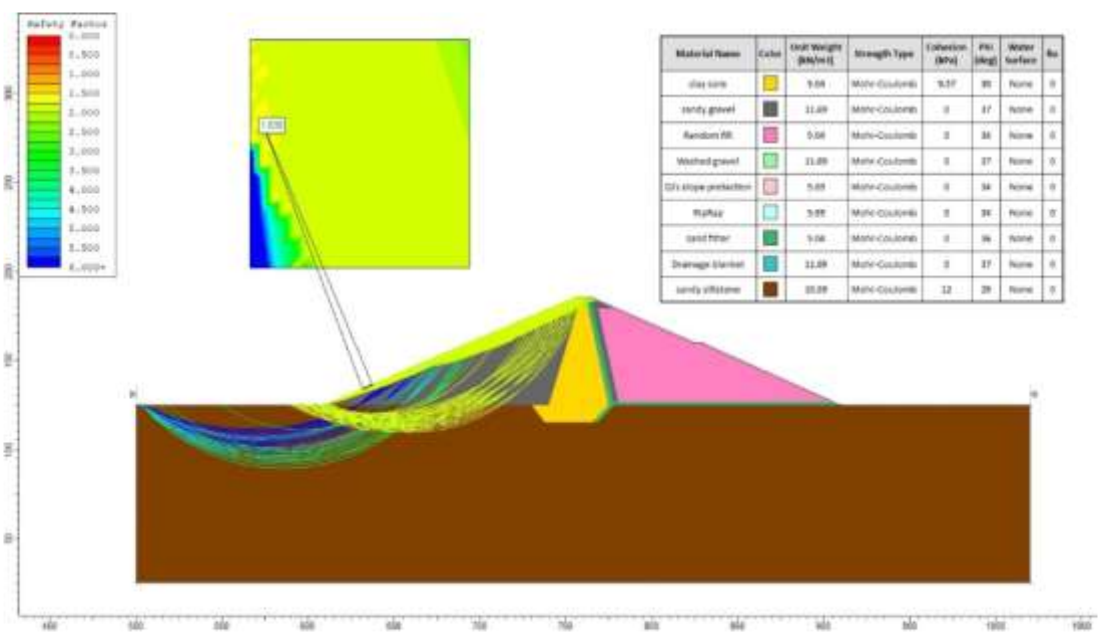

Figure 7: Deterministic Analysis W/O Water Table Fellenius Metho

FOS with water table: 0.696

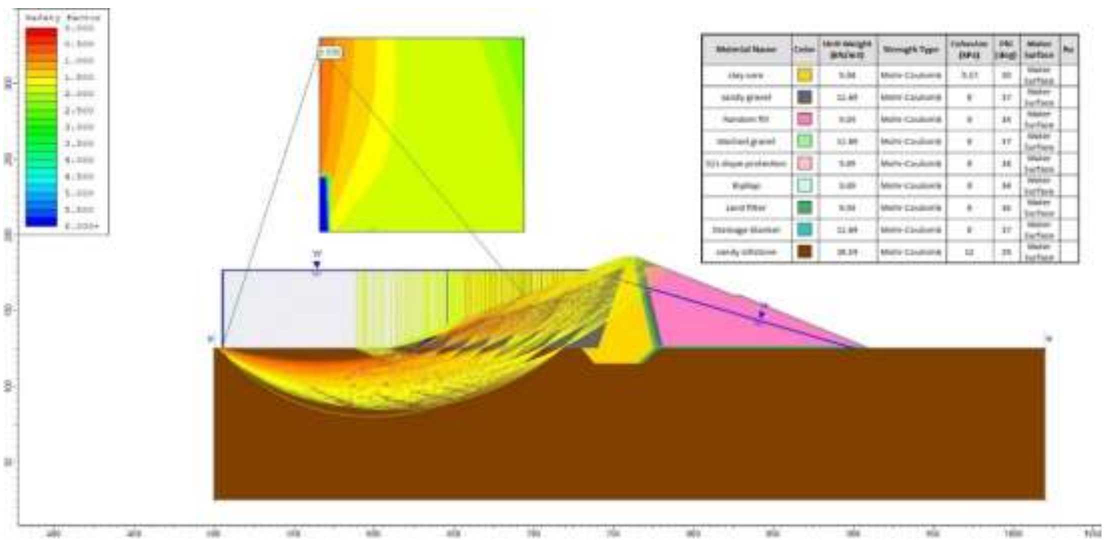

Figure 8: Deterministic Analysis with Water Table Fellenius Method

Discussion of Deterministic Analysis

We have done deterministic analysis by three different methods, such as Bishop, Fellenius & Janbu. First, it is performed without a water table to check whether Dam is stable after construction or not, so after analysis, FOS shows that the Dam is stable. After that, analysis was performed by adding a water table up to 50m. It indicates that Dam is failing as FOS lies below the limit. So, from the results, it is concluded that FOS decreases as water table height increases.

Table 5: Deterministic Analysis Results

	FOS (W/O Water table)	FOS (With water table)
Bishop Method	1.633	0.653
Janbu Method	1.632	0.593
Fellenius Method	1.630	0.696

Probabilistic Analysis

Using rainfall infiltration, probabilistic analysis has been done by three different methods: Fellenius, Bishop, and Spencer. We first entered a water level of 50 ft. and, after failing, a water level of 29.8ft.

By Bishop Method

At a water level of 29.8 ft.

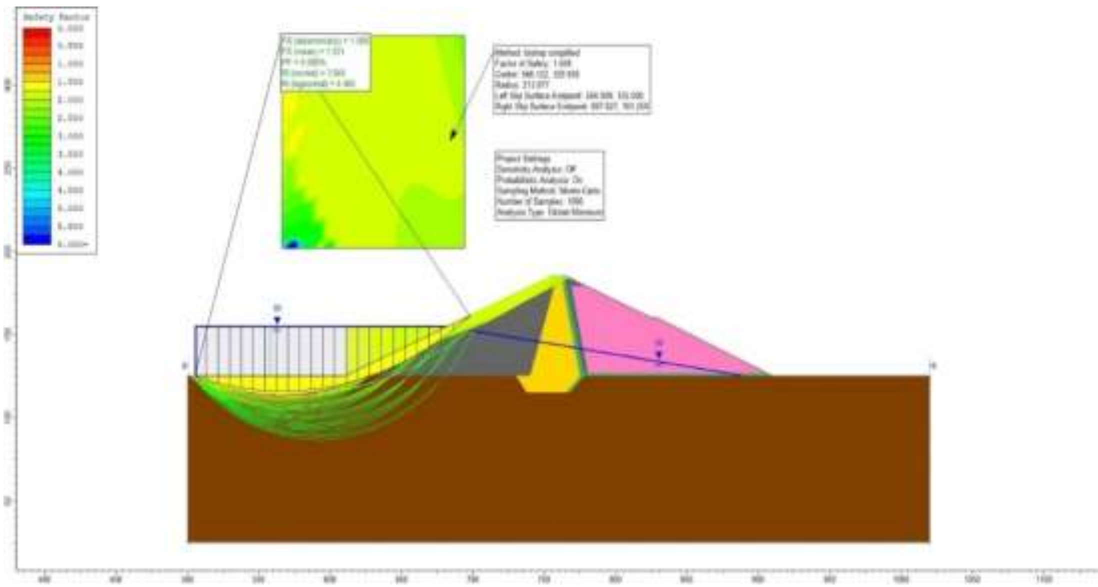

Figure 9: Probabilistic Analysis At 29.8 Ft. Water Table by Bishop Method

Relation between FOS and Reliability Index (R.I.)

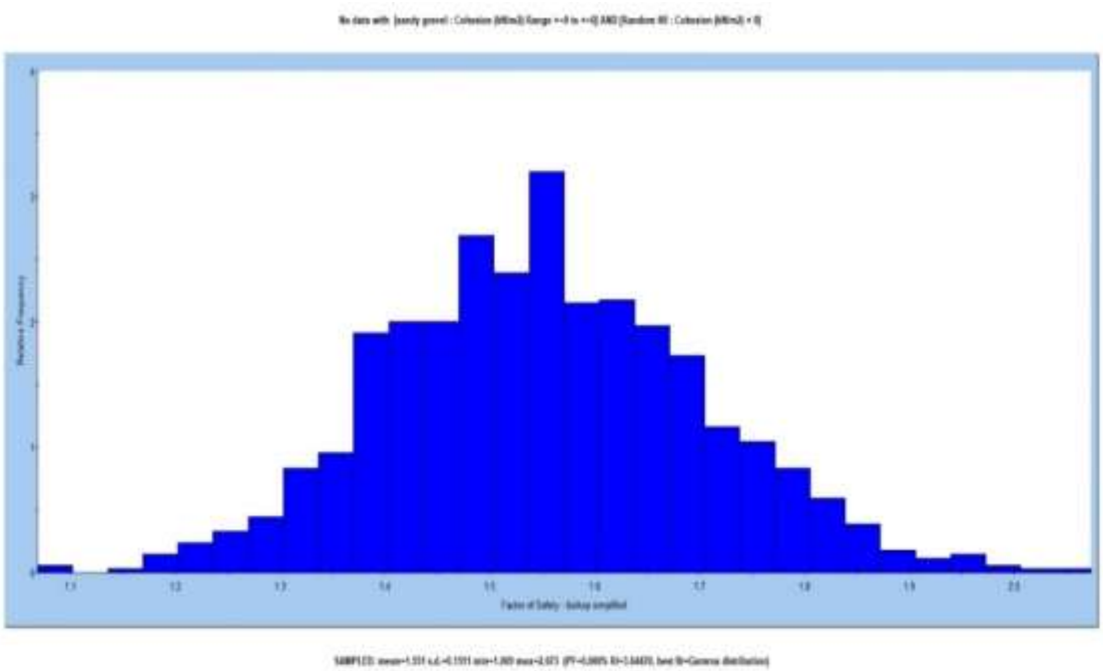

Figure 10: Histogram FOS Vs. Relative Frequency at 29.8 ft. by Bishop Method

At a water level of 50 ft.

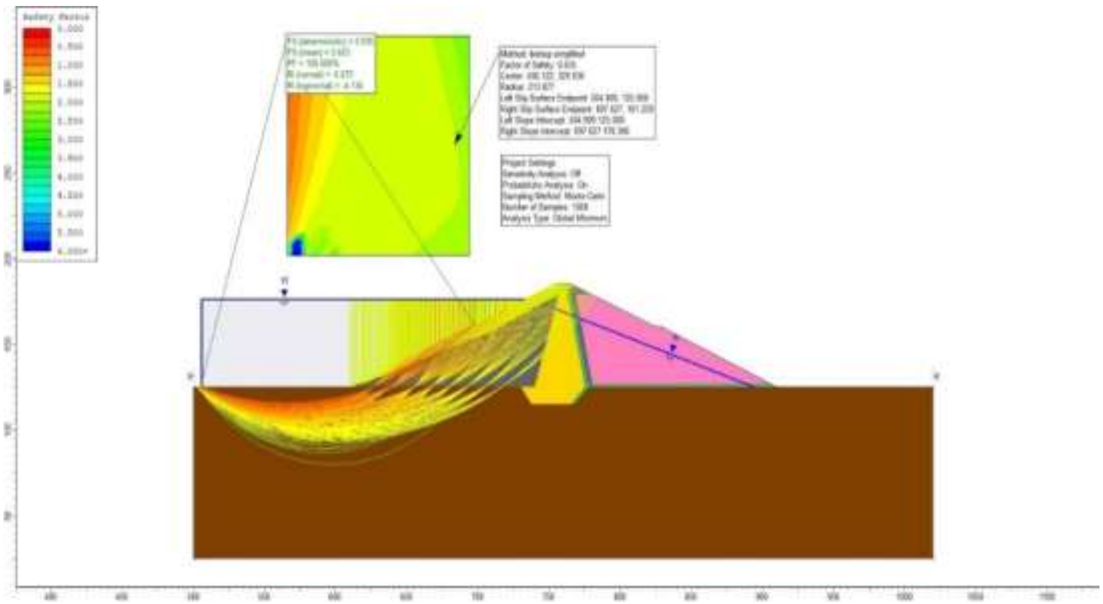

Figure 11: Probabilistic Analysis at 50 ft. Water Table by Bishop Method

Relation between FOS and Reliability Index (R.I.)

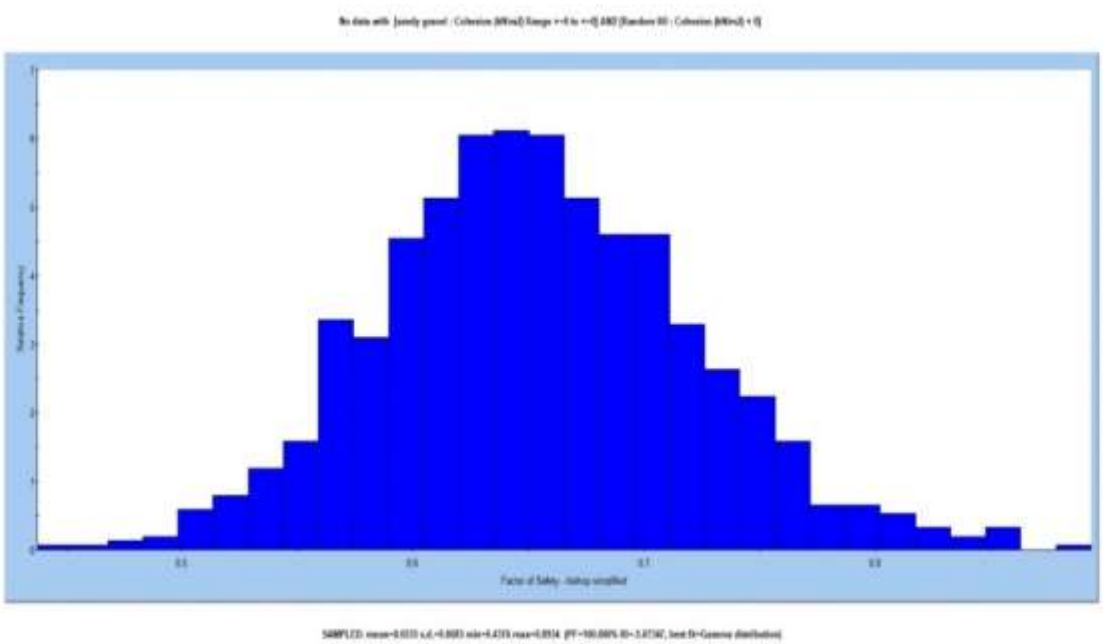

Figure 12: Histogram FOS Vs Relative Frequency at 50 ft. by Bishop Method

By Fellenius Method

At a water level of 29.8 ft.

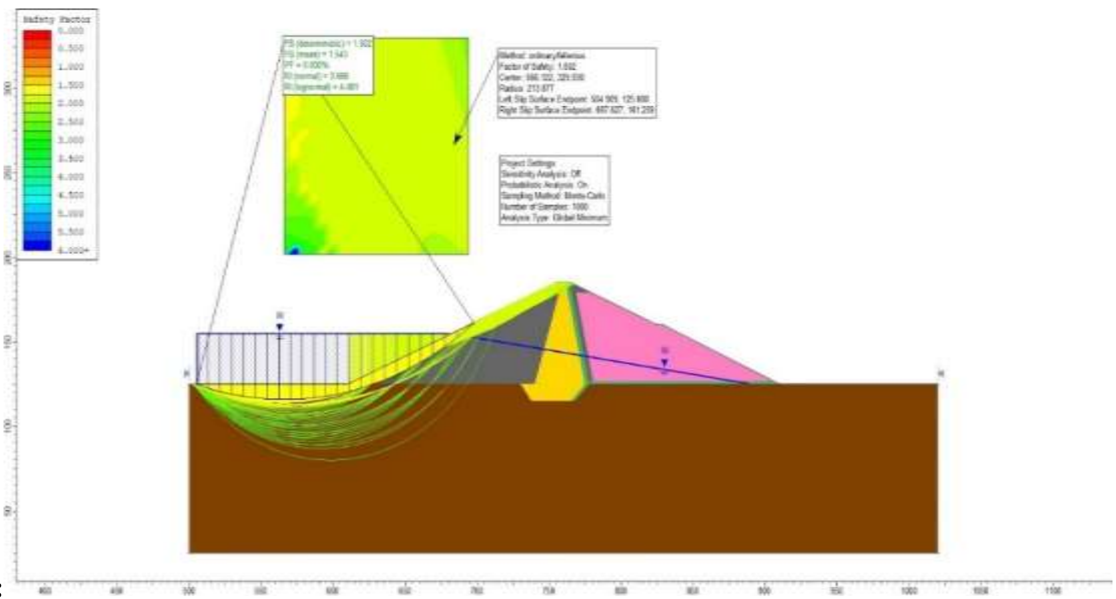

Figure 13: Probabilistic Analysis at 29.8 ft. Water Table by Fellenius Method

Relation between FOS and Reliability Index (R.I.)

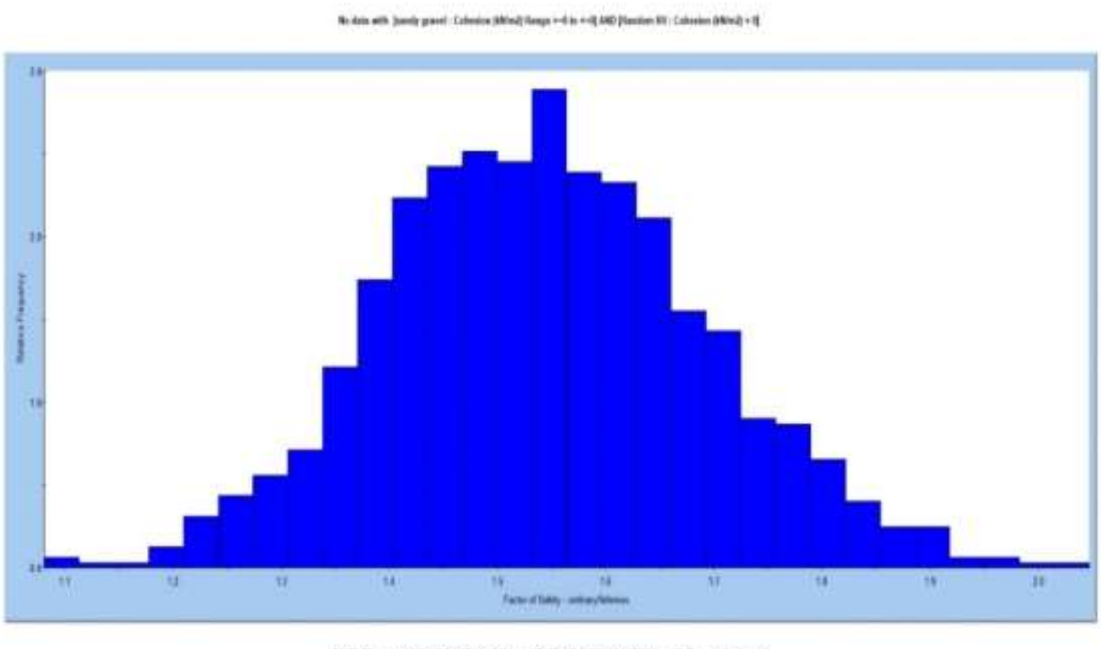

Figure 14: Histogram FOS Vs Relative Frequency at 29.8 ft. by Fellenius Method

At a water level of 50 ft.

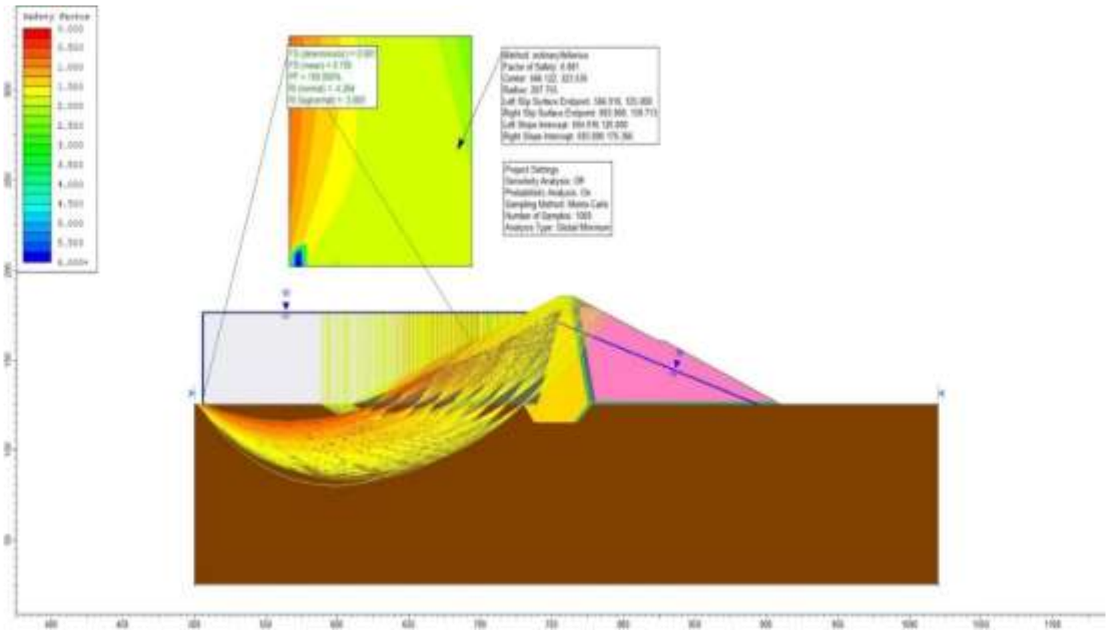

Figure 15: Probabilistic Analysis at 50 ft. Water Table by Fellenius Method

Relation between FOS and Reliability Index (R.I.)

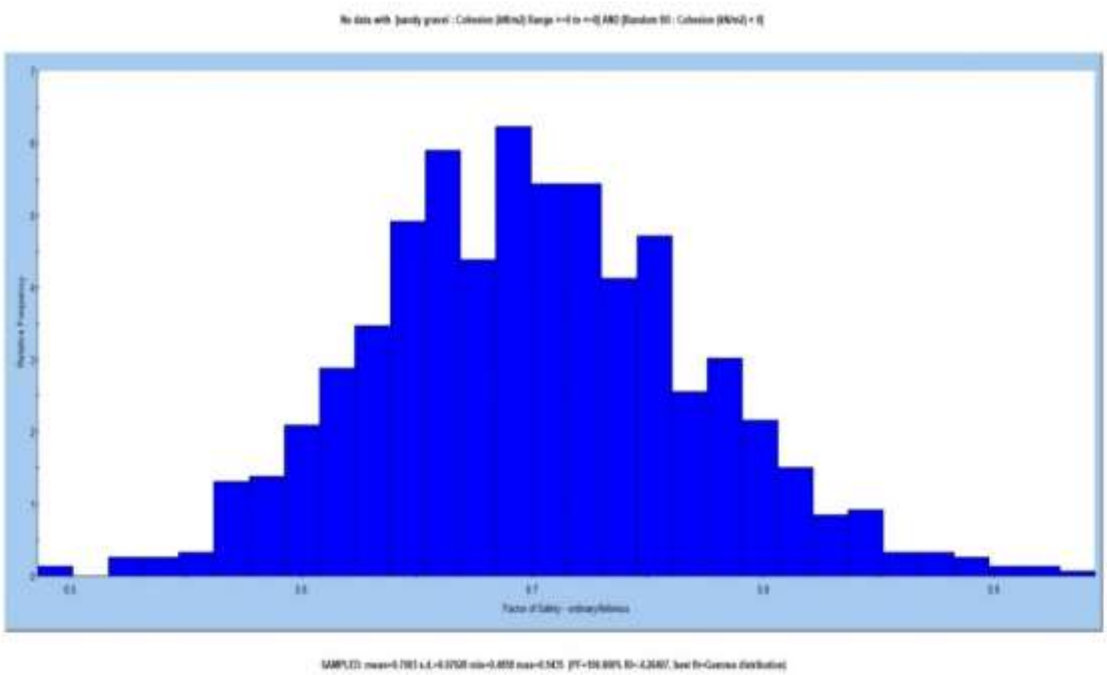

Figure 16: Histogram FOS Vs Relative Frequency at 50 ft. by Fellenius Method

By Spencer Method

At a water level of 29.8 ft.

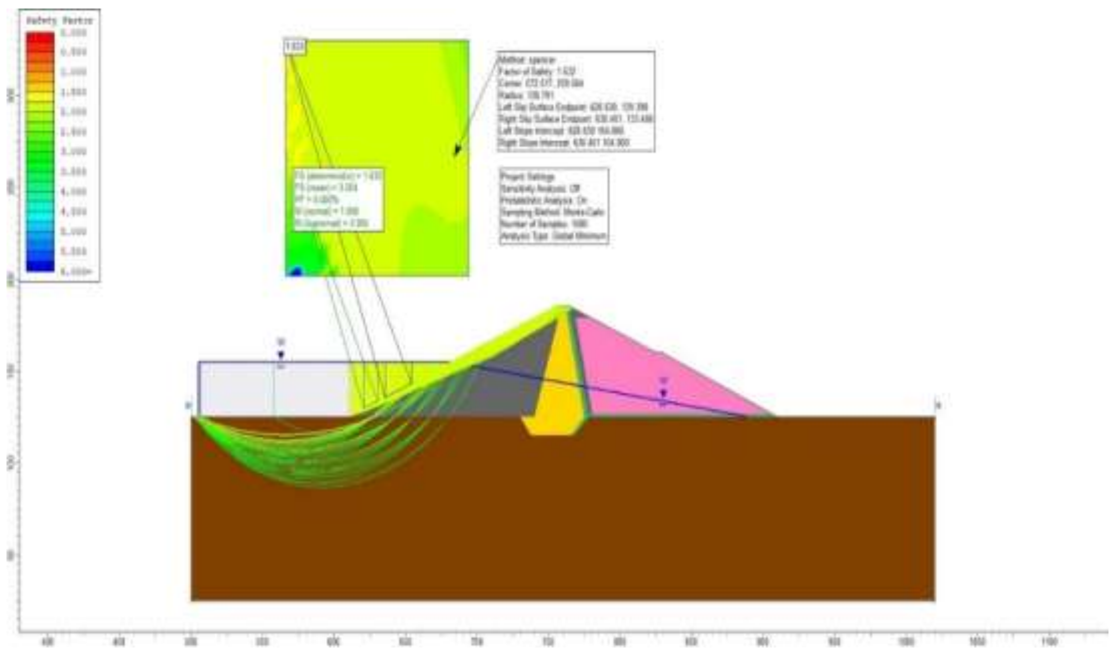

Figure 17: Probabilistic Analysis at 29.8 ft. Water Table by Spencer Method

Relation between FOS and Reliability Index (R.I.)

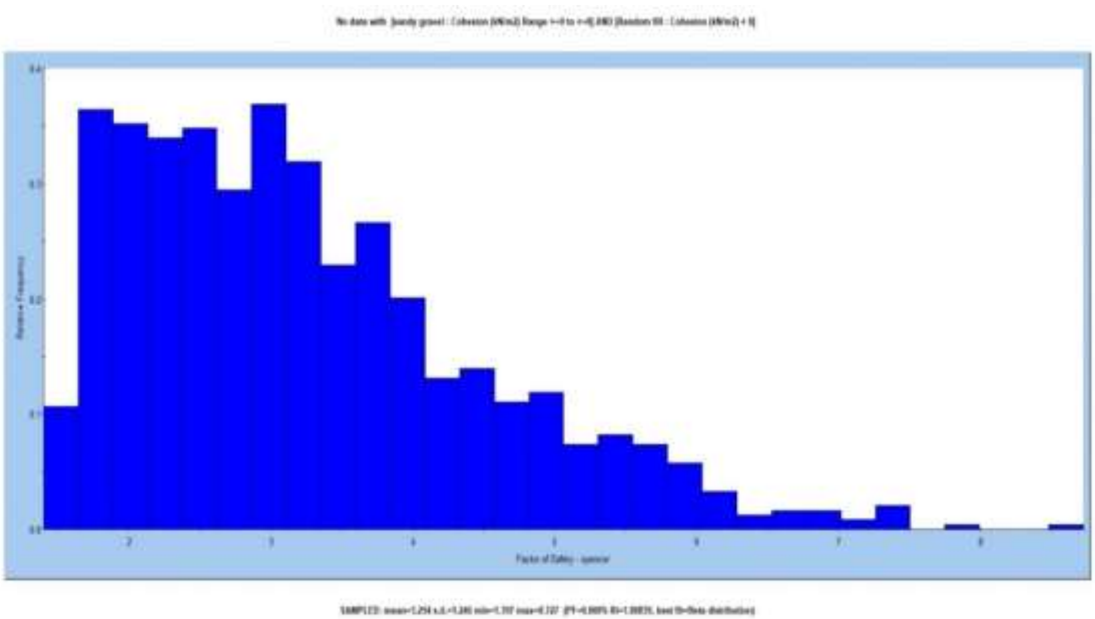

Figure 18: Histogram FOS Vs Relative Frequency at 29.8 ft. by Spencer Method

At a water level of 50 ft.

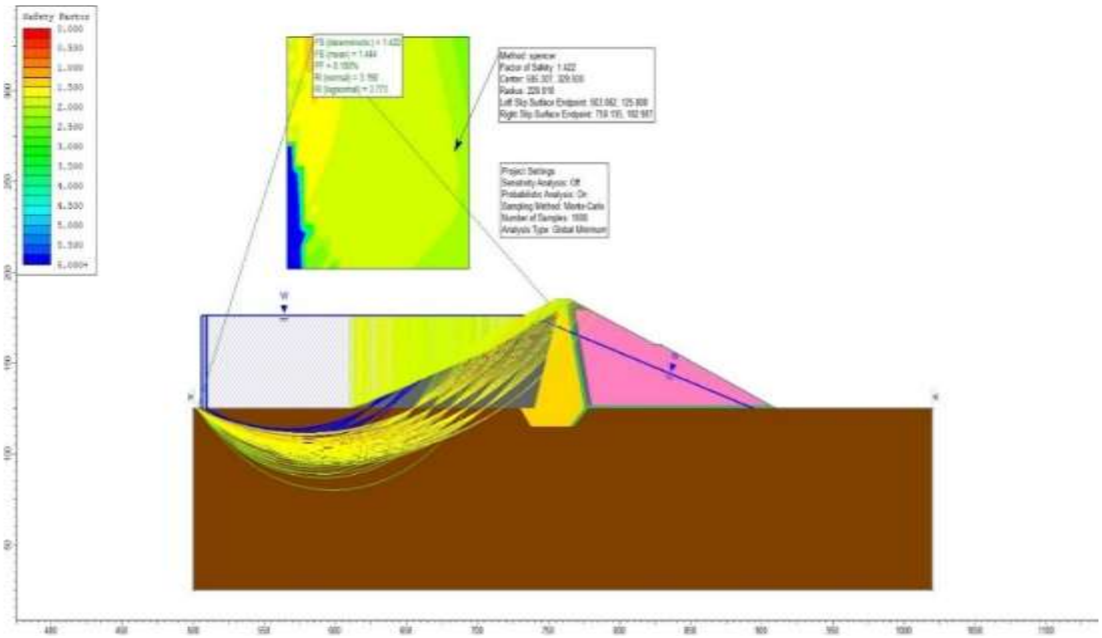

Figure 19: Probabilistic Analysis at 50 ft. Water Table by Spencer Method

Relation between FOS and Reliability Index (R.I.)

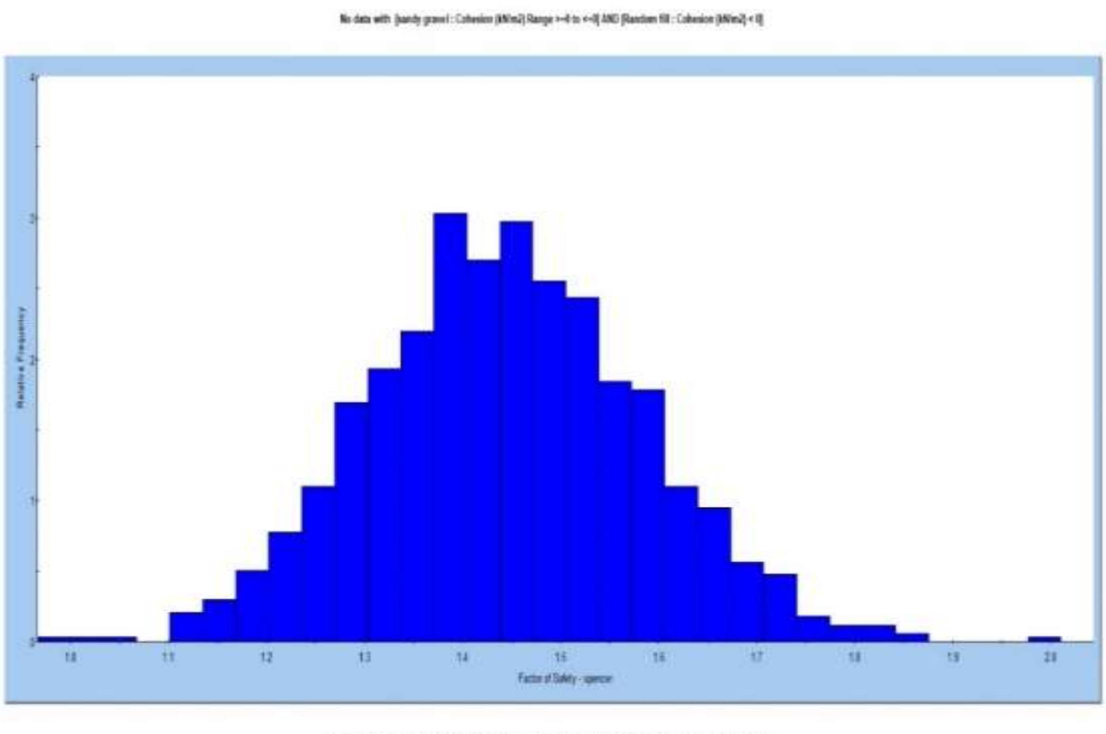

Figure 20: Histogram FOS Vs Relative Frequency at 50 ft. By Spencer Method

Discussion of Probabilistic Analysis

In probabilistic analysis with all three methods, it is observed that at 50 m water level height, the Dam is failing in all ways such that its FOS is under 1.5, but as we decrease the water level height, FOS increases. So, it is concluded that the water level maximum height on the designed Dam embankment could be 29.8m. Additionally, it has been found that the reliability index and the factor of safety are directly related. As RI increases, FOS also increases.

Table 6: Probabilistic Analysis

Water level of 50m		
	The Factor of Safety (FOS)	**Reliability Index**
Fellenius Method	0.681	-4.26
Bishop Method	0.635	-5.07
Spencer Method	1.422	3.19
Water level 29.8m		
	The Factor of Safety (FOS)	**Reliability Index**
Fellenius Method	1.502	3.66
Bishop Method	1.509	5.07
Spencer Method	1.632	1.80

Seepage Analysis

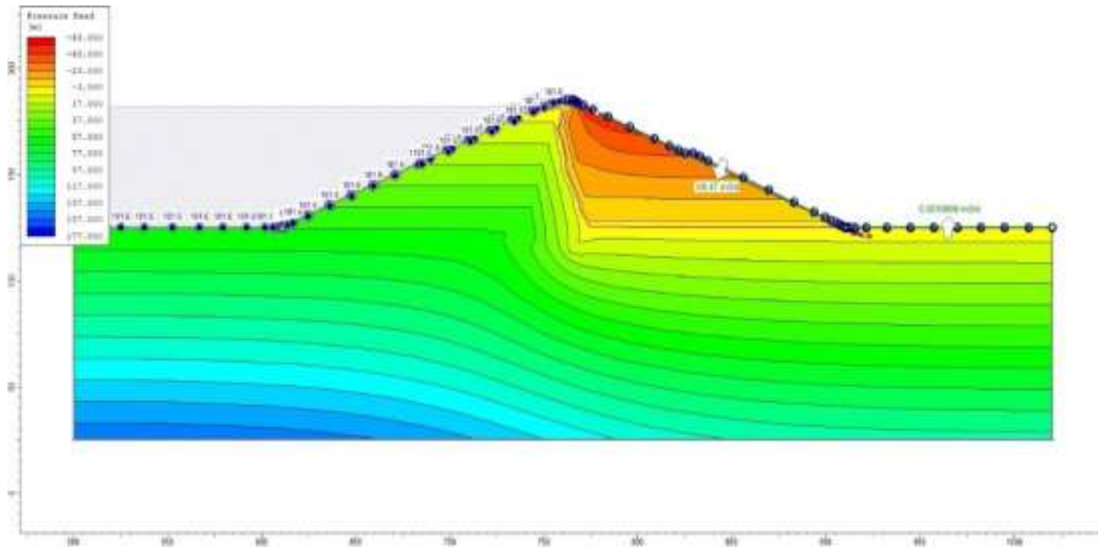

Figure 21: Seepage Analysis

In seepage analysis, at down flow discharge value comes out to be 60.47 m3/day. It is observed that seepage analysis does not directly affect the Dam embankment. It causes erosion which results in the moving of soil under the embankment of the Dam, and in the end, the Dam embankment fails.

Conclusion

A deterministic analysis is performed without a water table to check whether Dam is stable after construction or not, so after analysis, FOS shows that the Dam is stable. After that, analysis was performed by adding a water table up to 50m. It indicates that Dam is failing as FOS lies below the limit. So, from the results, it is concluded that FOS decreases as the water table height increases. In Probabilistic Analysis by using rainfall infiltration, it is observed that at 50 m water level height, the Dam is failing in all methods such that its FOS is under 1.5. After decreasing the water level to 29.8m, the Dam embankment passes, and FOS exceeds 1.5. In seepage analysis, the discharge value comes out to be 60.47 m^3/day.

Conflicts

The authors certify that they do not have any conflicting interests to declare.

Acknowledgment

The authors would like to express their appreciation to the Civil Engineering department at the NED University of Engineering and Technology for their support and assistance in carrying out this research.

References

1. Duncan, J.M., *Factors of safety and reliability in geotechnical engineering.* Journal of Geotechnical Engineering, 2000. **126**(4): p. 307-316.

2. Xiao, R., et al., *New insights into the 2020 Sardoba Dam failure in Uzbekistan from Earth observation.* International Journal of Applied Earth Observation and Geoinformation, 2022. **107**: p. 102705.

3. Bhutto, A.H., et al., *Parametric Analysis of an Embankment Dam's Stability*. Engineering, Technology & Applied Science Research, 2019. **9**(6): p. 5016-5020.

4. Alonso, E.E., *Risk analysis of slopes and its application to slopes in Canadian sensitive clays.* Geotechnique, 1976. **26**(3): p. 453-472.

5. Alitabar, A., R. Noorzad, and A. Qolinia, *Evaluation of the Instability Risk of the Dam Slopes Simulated with Monte Carlo method (Case Study: Alborz Dam).* Geotechnical and Geological Engineering, 2021. **39**(6): p. 4237-4251.

6. Duncan, J.M., S.G. Wright, and T.L. Brandon, *Soil strength and slope stability*. 2014: John Wiley & Sons.

7. Jansen, R.B., *Advanced Dam engineering for design, construction, and rehabilitation*. 1988: Springer Science & Business Media.

8. Novák, P., et al., *Hydraulic structures*. 2017: CRC Press.

9. Brinkgreve, R., S. Kumarswamy, and W. Swolfs, *Plaxis, Reference Manual.* PLAXIS bv, 2017.

10. Bashir, A., et al., *Understanding the Seepage Behavior of Nai Gaj Dam through Numerical Analysis.* Engineering, Technology & Applied Science Research, 2022. **12**(1): p. 8085-8089.

11. Zhang, L., Y. Xu, and J. Jia, *Analysis of earth Dam failures: A database approach.* Georisk, 2009. **3**(3): p. 184-189.

12. Kareem, I.R., A. Al-Adili, and H.H. Abdulla, *Study the Infiltration and Stability of the Earthfill Dams (Proposed Kashkan Dam as a Case study).* Kufa Journal of Engineering, 2013. **4**(2).

13. Chen, Q. and M. Tang, *Probabilistic analysis of slope stability of earth Dams during rainfall infiltration*, in *GeoFlorida 2010: Advances in Analysis, Modeling & Design*. 2010. p. 2022-2031.

14. Flores-Berrones, R., M. Ramírez-Reynaga, and E.J. Macari, *Internal erosion and rehabilitation of an earth-rock Dam.* Journal of Geotechnical and Geoenvironmental Engineering, 2011. **137**(2): p. 150-160.

15. Zeidan, B.A., et al. *Seepage and slope stability analysis of earth Dams*. in *ICOLD 2018 26th Congress–86th Annual Meeting*. 2018.

16. Ahmad, A., et al., *Re-Assessment of an Earth fill Dam using Finite Element Method and Limit Equilibrium Method (Case study of Latamber Dam, Pakistan).* Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 2020. **71**(2): p. 87-102.

17. Christian, J.T., *Geotechnical engineering reliability: How well do we know what we are doing?* Journal of geotechnical and geoenvironmental engineering, 2004. **130**(10): p. 985-1003.

18. Peck, R.B., *Advantages and Limitations of the Observational Method in Applied Soil Mechanics.* Géotechnique, 1969. **19**(2): p. 171-187.

19. Christian, J.T., C.C. Ladd, and G.B. Baecher, *Reliability applied to slope stability analysis.* Journal of Geotechnical Engineering, 1994. **120**(12): p. 2180-2207.

20. Tang, W., *Recent developments in geotechnical reliability*. Probabilistic methods in geotechnical engineering, 2020: p. 3-27.

21. Mostyn, G. and K.S. Li, *Probabilistic slope analysis—State-of-play*, in *Probabilistic methods in geotechnical engineering*. 2020, CRC Press. p. 89-109.