RELIABILITY ANALYSIS OF DAMPALIT MEGA DIKE USING MONTE CARLO SIMULATION AGAINST SLIDING FAILURE

*Isaiah Sam Bartolome[1] and Albert Griño, Jr.[1]

[1]Department of Civil Engineering, Adamson University, Philippines

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ABSTRACT: The main purpose of coastal defenses is to mitigate the effects of an increased rise in sea levels and the abrupt changes in storm surges brought upon by various uncertainties. Evaluation of the Dampalit Mega Dike's resistance against sliding failure using Reliability Analysis provides an avenue for considering these uncertainties that would affect the structural safety of the dike. In this study, random variables, including the angle of friction, water level, and wind speed, were considered as the parameters in determining the dikes' probability of failure. Wave action and storm surges were considered, which were vital since these would greatly affect the resistance of the dike. A deterministic approach was initially performed using PLAXIS 2D to compare the conventional design and analysis with a probabilistic approach. For the probabilistic method, both serviceability (SLS) and ultimate limit states (ULS) were evaluated with 100,000 iterations using Monte Carlo Simulation wherein results show a probability of a failure of 0.54 for SLS and 0.86 for ULS. The significant deviation from the acceptable value of x 10^{-3} to the computed values highlights a potentially critical issue in the structural system or the underlying assumptions used in the analysis. A high risk of failure in terms of sliding was concluded, however, biases were observed in the data since no correlations were found between the variables. Moreover, to increase the soil stability of the dike, an additional embankment on the seaward side was recommended to improve the resistance against sliding failure of the dike.

Keywords: Reliability analysis, Storm Surge, Monte Carlo Simulation, Probability of failure, Dike

1. INTRODUCTION

The rise of sea levels contributes to the increase in flooding, especially in Asian deltaic cities, which include Ho Chih Minh City, Jakarta, Tokyo, and Manila. Exposure to tropical cyclones, excessive groundwater extraction, and rapid urbanization leads to elevated flood levels, affecting the city's socioeconomic development. Furthermore, it is evident that there's a need for a more localized, probabilistic risk assessments that better account for uncertainties, as opposed to the deterministic design approaches currently prevalent in flood management practices [1]. By 2100, the global mean sea level will rise to 2.92 m. This will affect about 150 – 250 million people, especially those living near coastal areas and low-elevation areas [2]. According to the National Integrated Climate Change Database and Information Exchange System, or NCCDIES (2024), the Philippines is experiencing an exceptionally high rate of sea level rise of 60 centimeters, which is roughly three times faster than the global average of 19 centimeters, which puts 13.6 million Filipinos at risk. Climate models provide a range of predictions for future sea level rise, reflecting different greenhouse gas emission trajectories.

The city of Manila in the Philippines is considered one of the most vulnerable megacities in Southeast Asia in terms of the rapid rise in sea levels. The Dampalit Mega Dike, which is located in Barangay Dampalit, Malabon City, is an 8.6-kilometer mega dike that was constructed for protection against flooding of the surrounding areas [3]. The Dampalit Mega Dike is important for Malabon's safety and economy. Failure could lead to widespread flooding, endangering lives and disrupting the economy.

Flooding in coastal areas is a predominant problem especially with the Philippines which is an archipelagic country. The city of Manila is located near bodies of water that are prone to extensive flooding due to increased precipitation which leads to increased runoff that is insufficient for most urban watersheds [4] and damage to coastal defenses [5].

Uncertainties are dominantly present in every structure constructed, and these affect its overall function. In the Philippines, the design of numerous structures, including flood defenses, was mainly based on a deterministic approach, which only considers normal ranges based on structural codes. The problem with a purely deterministic designed structure is that the data is gathered under various environmental and material conditions, including imposed loads and material properties. The utilization of statistics and probability in the design of the structure is beneficial in considering the uncertainties that are present in the location [6]. This study addresses notable gaps in existing research by integrating a probabilistic framework that encompasses effects of local sea level rise and subsidence data with structural performance analysis

of existing flood defenses in Manila.

The situation poses a significant cause of concern for the city and its residents, and prompt action is essential to mitigate the effects of this impending crisis. This study proposed a method of assessing Manila's coastal flood defenses using reliability analysis by assessing the earth sea dikes that are critical for safeguarding low-lying regions and assets from flooding, erosion, and landslides. However, the impending threat of climate change and rising sea levels are impacting the hydraulic conditions and structural integrity of these defenses. To effectively manage risks and optimize maintenance and inspection strategies, it is imperative to conduct reliability analysis using Monte Carlo Simulation for risk analysis of Manila's coastal defenses.

2. RESEARCH SIGNIFICANCE

The relevant information of this study would help benefit local government authorities and community stakeholders as they contribute to informed decision-making, policy formulation, and the overall resilience of Manila Bay Coastal Defenses. The present study's outcomes would assist LGUs in identifying gaps and challenges inherent in their existing risk management practices. It provides insights into how risk management strategies in Manila City and neighboring areas can be effective. This study can serve as a valuable reference for establishing performance functions that address serviceability and ultimate limit states for sliding of sea dikes.

3. PROBABILISTIC APPROACH

Probabilistic structural analysis is defined as the art of formulating mathematical models wherein one can acquire results concerning the probability of a structure behaving in a definite manner through calculations. It involves analyzing the behavior of a structure using random material properties and the effect of an external factor on the stability of a structure with random or incomplete known properties [7]. Reliability analysis provides an advanced and more accurate calculation of structures since safety factors from the deterministic method often offer a safety margin that is relatively not 100% safe due to the effects of uncertainties [8].

3.1 Random Variables

The presence of uncertainties in various parameters used in the conventional design and analysis contributes to the difficulty in providing a safe and resilient structure through a deterministic approach [9]. This is why establishing a reasonable basis is beneficial, as it provides a means of assessment that can be fulfilled through the evaluation of its reliability and probability of failure.

Failure does not always mean losing the function of a structure; rather, it signifies that the structure does not meet the expectations based on its design.

For this study, the random variables considered were based on the primary phenomenon of sliding failure and the effects of storm surges on the dike. The random variables chosen for this study include the sea level h, angle of friction ϕ, and wind speed V_s. These random variables were evaluated since these are where uncertainties can be readily observed, and abrupt changes in these factors can contribute to the overall safety of the dike [10]. Furthermore, since the location of the structure under consideration is near a flood-risk area, the sudden changes in sea levels will affect its stability to some extent. Since the main concern of this study is the strength, it is best to provide an assessment of the present situation of the Dampalit Mega Dike using reliability analysis.

3.2 Loads and Forces

3.2.1 Dead loads and live loads

In the case of the mega dike, the dead load is composed of the weight of the dike itself and the utilities installed on top of it, with the weight of concrete equal to 24 kN/m^3. Moreover, the live loads are the maximum loads perceived to occupy the structure in a specific duration of time, which includes the human occupancy and moving loads brought upon by vehicles.

3.2.2 Lateral earth pressure

At every possible point in the soil mass is susceptible to failure due to the stresses that it experiences. This condition is known as plastic equilibrium, and Rankine (1857) investigated this phenomenon and formulated Rankine's theory of earth pressure as shown in Eq. (1).

$$K_a = \frac{\sigma'_a}{\sigma'_o} = tan^2\left(45 - \frac{\phi'}{2}\right) \tag{1}$$

$$\frac{\sigma'_p}{\sigma'_o} = K_p = tan^2\left(45 + \frac{\phi'}{2}\right) \tag{2}$$

On the other hand, Eq. (2) shows the calculation for the effective lateral earth pressure $\boldsymbol{\sigma'_p}$ which is the major principal stress that occurs on the soil surface. Ultimately, when the retaining wall is progressively pushed towards the soil mass, it will reach a certain point where failure will occur.

In Coulomb's (1776) theory, the failure surface of the soil is considered a plane and friction on the wall is considered. Eqs. (3) and (4) show the calculation for active and passive earth pressures, respectively.

$$P_a = \frac{1}{2}K_a\gamma H^2 \tag{3}$$

$$P_p = \frac{1}{2} K_p \gamma H^2 \qquad (4)$$

3.2.3 Hydrostatic pressure

Hydrostatic forces are composed of a vertical downward and upward component (uplift or buoyancy) and a lateral component, which can be resolved into an upward or downward and horizontal load depending on the geometry of the contact surface and the hydrostatic pressure distribution. The hydrostatic pressure is given by Eq. (5).

$$P = 0.5 \gamma_w h A_b \qquad (5)$$

Where A_b is the projected area considering 1 m. strip, h is the sea level, and γ_w is the unit weight of water.

3.2.4 Wave loads

Dikes are most likely to experience various loads, including water pressure, soil weight, and seismic forces, which should be primary considerations when it comes to its design. The behavior of dikes under varying load conditions must be considered by engineers to provide a sufficient and effective design [11].

The magnitude of wave forces kN/m^2 is 10 or more times higher than that of wind forces and other forces acting on a building or other structures under design conditions. Consequently, design must consider the increase of the elevation above that of the wave crest to provide sufficient protection from the impacts of wave action [12,13]. Moreover, elevated structures must also be designed for larger magnitudes of wave forces that can act on the foundation and other supporting structures. The wave action on the dike is defined in Eq. (6).

$$W_A = \frac{1}{2} \rho_w C_d A_b V_s \qquad (6)$$

Where C_d is the drag coefficient and V_s is the wind speed based on acquired data.

3.2.5 Storm surge loads

This type of load, in combination with an increase in tides, results in a dramatic increase in sea levels, causing inundation on coastlines and possible damage to offshore structures, including dikes. The height of storm surges may vary depending on the meteorological conditions experienced in a specific area. It may reach up to 28 feet high, as with Hurricane Katrina, which hit the coastal areas of Louisiana and Mississippi in the United States of America [14,15]. Eq. (7) defines the calculation of storm surge loads.

$$SL = \frac{1}{2} \rho_{air} A V s^2 \qquad (7)$$

3.3 Performance Function

The performance function or limit state function $g(X)$ is an expression used to identify the safe and unsafe zones for R (resistance of the structure) and S (load on the structure). Structural conditions are set to provide a depth analysis of the performance function based on the established random variables. Two structural conditions will be considered for this study, namely the Serviceability Limit State (SLS) and the Ultimate Limit State (ULS). SLS describes that the failure of the structure is based on the loss of serviceability, which doesn't imply a valuable impact on the overall safety of the structure. On the other hand, the ULS dwells more on the structural integrity and safety of the structure, which may eventually lead to complete failure [16].

3.4 Monte Carlo Simulation

Simulations governing both systems of physical and mathematical relations are the main objective of Monte Carlo Simulation. The Monte Carlo Simulation or Monte Carlo Method involves the generation of random events through a computer model wherein the procedure is done multiple times. The occurrence number for a specific condition set by the researcher is then counted and recorded.

The probability of failure of the system can be calculated through the integration of the random variables in a performance function. In some instances, it would be hard to determine the probability of failure through analytical methods since some boundaries of the integral are not known. The use of reliability methods, specifically Monte Carlo Simulation is more applicable for data sets that are relatively small [17].

The Monte Carlo Simulation is a highly regarded statistical technique that assists organizations in effectively managing risk and making informed decisions when faced with uncertain situations. This powerful tool can be utilized in disaster risk management by simulating a significant number of random variables to analyze the potential outcomes of a complex system. By generating a comprehensive set of individual realizations of sea level time series, decision-makers can leverage descriptive statistics to understand the probability and consequences of disasters. As a result, they can implement more effective risk management strategies [18].

4. METHODOLOGY

This study utilized various uncertainties that can affect the structural integrity of the dike. This includes the effects of storm surges, which are not common in the design of the dike. The occurrence of uncertainties, which are determined through various historical data and reports, is used to determine the

probability of failure due to sliding phenomena through the evaluation of the limit state equations using Monte Carlo Simulation.

Moreover, the evaluation of the Dampalit Mega Dike considers the effect of storm surge as the ultimate load that would affect the structure. The random variables that were considered are the angle of friction, sea level, and wind speed, and these are incorporated in the resistance and loads of each limit state equation. The values for these parameters were set based on the simulations performed on the data collected, and the results are used to calculate the probability of failure of the dike.

4.1 Data Gathering

The main sources of data for this study came from the geotechnical investigation report which was obtained from the Department of Public Works and Highways (DPWH), the sea level data, which was requested from the local government of Dampalit, and the wind speed data were obtained from Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAG-ASA).

4.2 Deterministic Method

In the Philippine setting, the common method used in the design of most buildings and infrastructures is governed using a deterministic approach. This is through the use of various codes for design and analysis, which includes the NSCP and other codes which are vital in providing a safe and resilient structure. These codes were mostly based on theoretical analysis and experimental models in which several assumptions are made [19]. According to Skrzypezak, Slowik, and Buda-Ozog (2017), a purely deterministic approach cannot completely define the reliability and safety of a structure since it is mostly based on a single globally used factor and does not take into consideration the effects of uncertainties with regards to the load and strength assessments provided by the structure.

This study employed deterministic and probabilistic approaches to accurately represent failure due to the sliding of the Dampalit Mega Dike. The study utilized PLAXIS 2D software for the structural analysis of the dike.

4.3 Probabilistic Method

Several parameters were not considered in the deterministic method; thus, it was difficult to provide an overall assessment of the safety of the dike. Therefore, reliability analysis must be done to assess the structure thoroughly. Random variables were viewed as the governing parameters in quantifying uncertainties and risks that a system would experience. The first step in determining the

structure's probability of failure and reliability index was to identify the possible variables that would affect the overall safety [20].
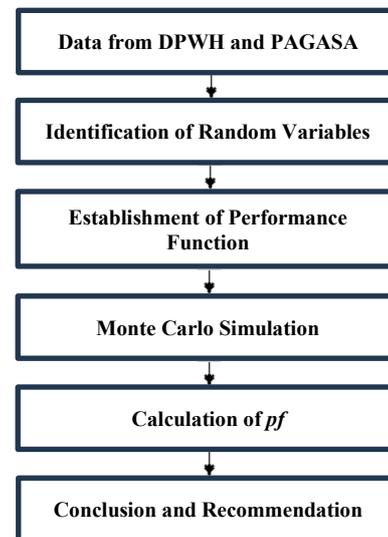

Fig. 1 Theoretical Framework

This study's theoretical framework is presented in Fig. 1. In this study, pre-existing mathematical models were considered for the selected random variables wherein the angle of internal friction followed a log-normal distribution while both sea level and wind speed followed a Weibull distribution as presented in Table 1. The mean and coefficient of variation were derived from the data acquired, which were then used to determine the distributions by performing simulations using MATLAB.

Table 1 Distribution of random variables

Random Variable	Distribution	Mean, μ	Coefficient of Variation, COV
Angle of internal friction, ϕ	Log-normal	27.19°	0.001°
Sea level, h	Weibull	10.07 m	0.002 m
Wind speed, V_s	Weibull	2.87 m/s	0.198 m/s

Calculation of probability of failure

This study considers the sliding failure mechanism's effect on the dike's safety with the impending rise of sea levels. The SLS and ULS equations for the sliding failure mechanism is defined in Eq. (8) and Eq. (9), respectively.

$$g(X) = F_k - (P_h + W_A + P) \tag{8}$$

$$g(x) = F_k - (P_h + W_A + P + S_L) \tag{9}$$

Where F_k is the sliding force or Law of Kinetic Friction derived from Amonton's and Coulomb's Law of Friction. The sliding force acted as the

resistance of the dike; it was used for both the serviceability and ultimate limit state equations. The load for SLS was based on the summation of the applied loads on the structure which includes lateral earth pressure P_h, wave action W_A, and hydrostatic force P while for that of the ULS.

In relation to the factor of safety, the probability of failure can be defined as the probability where the factor of safety falls below 1.0 if there are adverse effects of certain variables present in the calculations [21] which is shown in Eq. (10).

$$Pf = P(S > R) \qquad (10)$$

This study utilized 100,000 simulations for both the random variables and performance functions to be able to generate several data points. This would provide a good balance between obtaining increased accuracy and calculation duration for the equations. Moreover, it has been a common practice to use 100,000 simulations in performing the Monte Carlo Simulation wherein larger numbers lean to a more statistically reliable result [22].

The results for both the deterministic and probabilistic methods would provide reliable results that would support the occurrence of failure on the dike. Determining the failure points of the dike using PLAXIS would provide the necessary results to attest to the decrease in safety in terms of sliding. Moreover, probabilistic methods using reliability analysis would present the probability of failure due to the presence of uncertainties in the environment.

5. RESULTS AND DISCUSSION

5.1 Results of PLAXIS 2D

The initial results of the deterministic method using PLAXIS 2D, as seen in Fig. 2, show a significant displacement of 2.045×10^{-3} m., mostly due to hydrostatic forces and lateral earth pressure applied on the dike. The red regions represent the failure points where increased values of hydrostatic forces can cause the displacement of the soil beneath the dike, leading to failure.
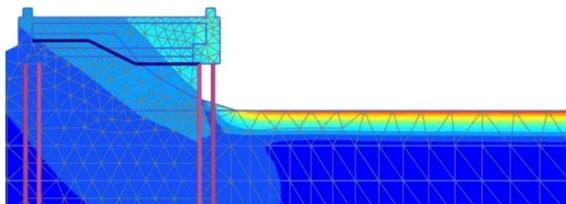

Fig. 2 Result of PLAXIS 2D analysis (total displacement of Dampalit Mega Dike)

The collapsed portion of the dike is due to the uplift pressure caused by the sea water, causing instability in the bottom-right part of the dike.
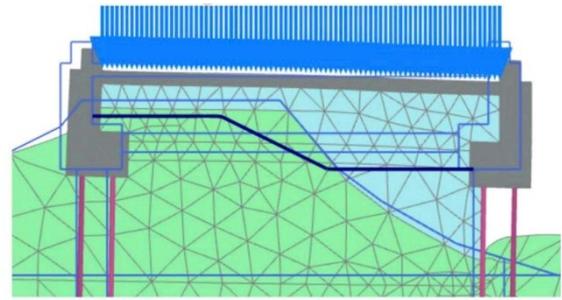

Fig. 3 Result of PLAXIS 2D analysis (deformed mesh)

Fig. 3 presents the deformed mesh of the dike upon the application of necessary loads. Based on the results, there is an evident failure on the seaside of the dike where possible sliding is due to increased pressure brought by both hydrostatic and lateral earth forces on the structure. Lack of sufficient support or increased soil stability caused the structure to fail at that specific point, especially with the effects of storm surges, which can cause higher wave impact, which weakens the soil [23].
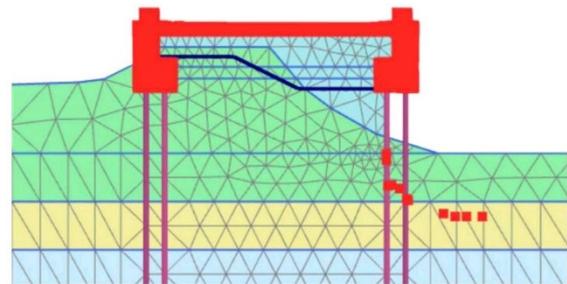

Fig. 4 Results of PLAXIS 2D (failure points)

Based on the results of PLAXIS 2D, the software indicates that the dike would slide by about 0.002045 meters or 2.045 mm. towards the seaside. PLAXIS 2D also indicated that the "soil body seems to collapse" as presented in Fig. 4 which is due to the uplift pressure caused by the sea water causing instability in the bottom-right part of the dike. The steepness of the topography of the soil where station C0+040.00 is situated, the soil could not handle the weight and forces applied on the dike, which resulted in its sliding.

5.2 Reliability Analysis

The gathered data for the angle of friction, wind speed, and water level were simulated 100,000 times to properly provide a reliable distribution which was utilized for the calculation of the probability of failure. It was important to identify the distribution of these random variables through their mean and

coefficient of variance to be able to appropriately apply the right method of estimate for the performance functions. The distribution of these random variables is presented in Fig. 5.

The statistical parameters derived from the analysis were implemented in MATLAB, where custom-developed code facilitated simulations and probabilistic assessments. The methodology relied on the Monte Carlo Simulations, enabling a comprehensive evaluation of system performance by quantifying the effects of variability and uncertainty in the input parameters. This approach allowed for robust predictions of system behavior under diverse conditions and informed decision-making regarding soil-structure interaction and environmental considerations.

The probability of failure was calculated for each limit state equation and its corresponding resistance and loads. To provide an accurate result of the probability of failure in multiple occurrences presented by each simulated value of the random variables, 100,000 simulations were also done using Monte Carlo Simulation for both SLS and ULS. It must also be considered that the computation of the load combinations followed a modified loading combination since the National Structural Code of the Philippines does not have a specific section for dike structures.

Based on the results, it is evident that there is no direct correlation between resistance and load. Moreover, a change in the load would not affect the resistance of the dike since both acts independently of each other.

The results of the calculations for the probability of failure for both SLS and ULS using MATLAB are presented in Figs. 6 and 7.
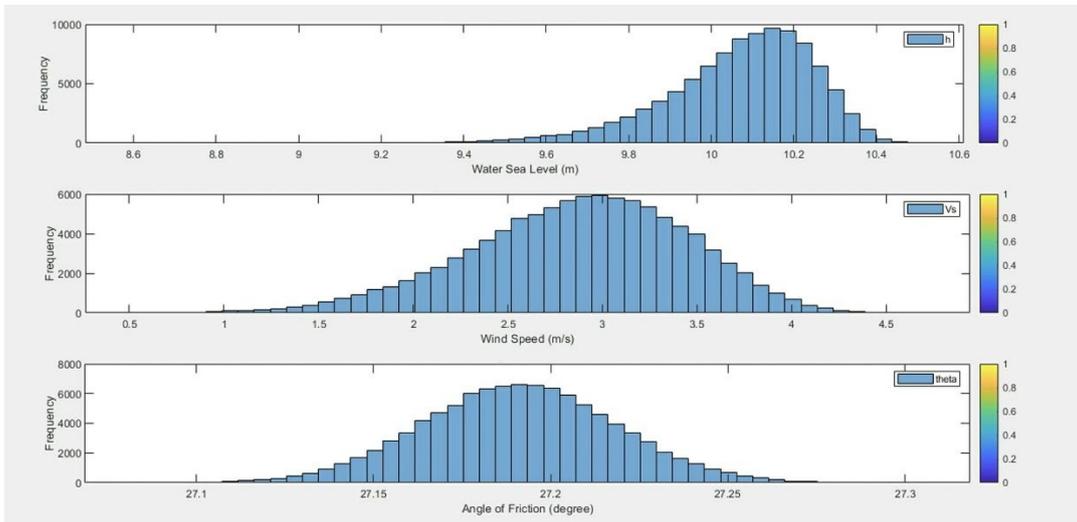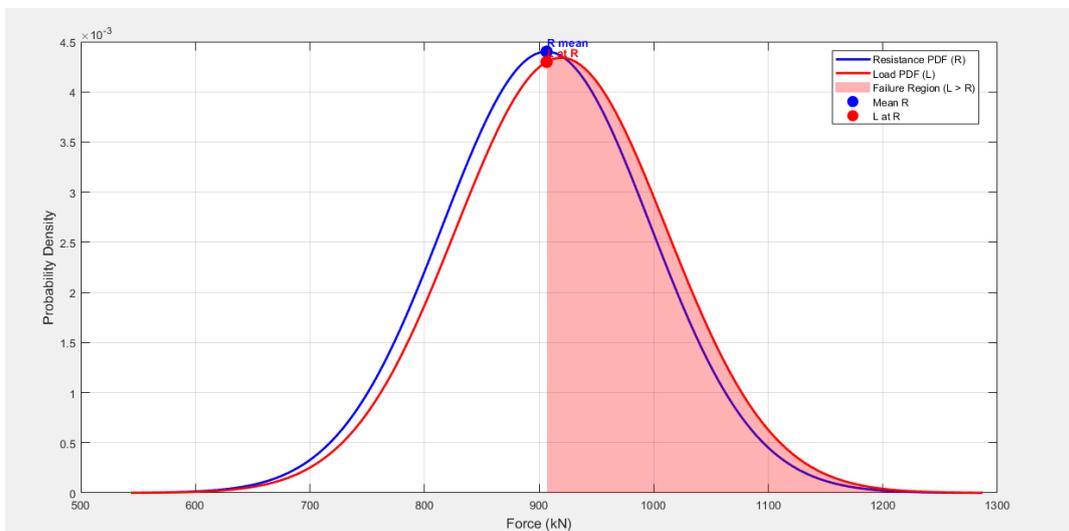

Fig. 5 Histogram of random variables

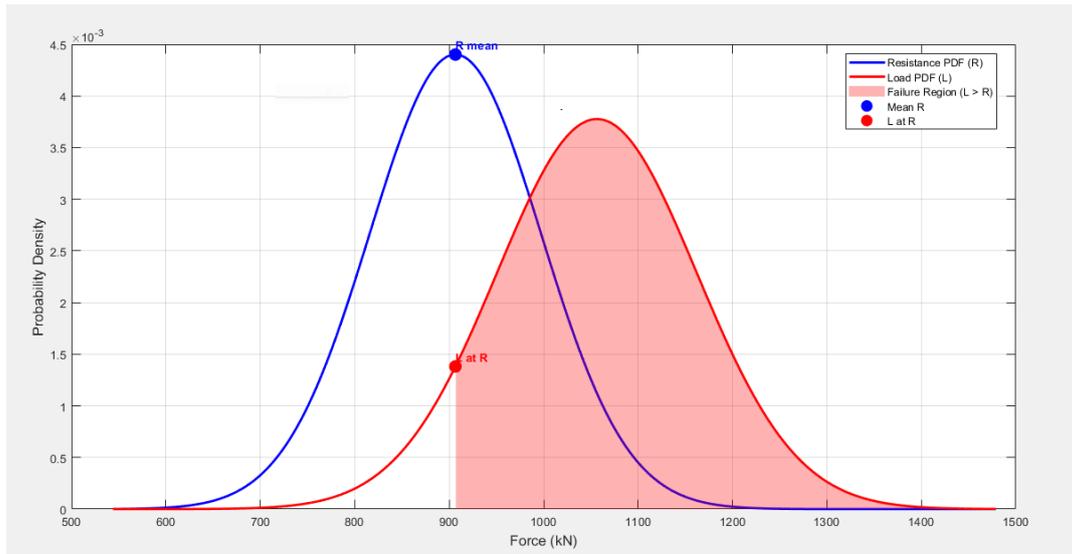Fig. 6 Probability of failure for SLS

Fig. 7 Probability of failure for ULS

The probability of failure of the dike against sliding failure was calculated using 100,000 simulations with the equation $Pf = P(S > R)$ which is determined by a normal cumulative distribution that resulted in $Pf = 0.54$ for SLS and $Pf = 0.86$ for ULS. Based on the graph, the failure point for the resistance is determined to be at around 3.1 x 10^{-3} for both SLS and ULS, while that of the load is estimated to be around 1,300 kN of force.

Based on the results of both deterministic and probabilistic methods, it is evident that the water level, wind speed, and angle of friction would affect the dike's sliding resistance. These uncertainties would affect the overall stability of the Dampalit Mega Dike, especially with the capacity of the soil to prevent the sliding of the dike. Varying degrees of pressure brought by the hydrostatic force on the dike induce displacement of the soil where the dike is constructed.

According to Zhang, et al (2017), a great factor that affects the destabilization of a dike is the combined effects of normal hydrostatic force exerted by seawater and the increased shearing effect from overtopping flows. The abrupt increase and decrease in wave pressure affects the resistance of the dike, resulting in sliding and eventually failure. Coastal dikes are most vulnerable to drastic changes in hydrostatic and hydrodynamic loads.

The knowledge and understanding of wave load and storm surges are typically not common [24]. Furthermore, overtopping waves in dikes is considered a detrimental threat to both properties and lives in coastal areas. The inclusion of a probabilistic method in the analysis of structures, especially with dikes, can provide a more conservative and resilient design.

The results for the probability of failure for SLS shows a value of 0.54 while that of the ULS shows a

value of 0.86. Such a result suggests that the structure under consideration is highly unreliable and fails to meet the minimum safety requirements. Moreover, a result that shows an almost 100% failure is very unlikely, and certain parameters must be checked to ensure the viability of the results.

According to Li and Yang (2023), the significant deviation from the acceptable value of x10^{-3} to the computed value of 1.000000 highlights a potentially critical issue in the structural system or the underlying assumptions used in the analysis. This discrepancy may arise from inadequacies in design parameters, improper material properties, or unforeseen environmental loads. It underscores the necessity for an immediate reassessment of the design, including a comprehensive review of the input parameters, modeling assumptions, and boundary conditions. These findings emphasize the critical importance of accurate reliability analysis in engineering design. The ability to detect such high probabilities of failure ensures that corrective measures can be implemented to prevent catastrophic outcomes. Future work should focus on refining the computational framework, validating input data, and exploring alternative design solutions to align with acceptable safety margins.

6. CONCLUSION

Based on the analysis conducted on the Dampalit Mega Dike, this study assessed the likelihood of failure due to sliding using both deterministic and probabilistic methods. The deterministic analysis carried out using PLAXIS 2D revealed that the dike would experience sliding with a minimal displacement of 0.002 meters under current conditions. The displacement was so minimal that it was nearly unnoticeable, suggesting that the structure remains functional under serviceability loads.

This indicates that, based on static loading conditions, the dike is still operational and capable of performing its intended function. However, the results of the probabilistic analysis, which included random variables such as angle of friction, water level, and wind speed, showed that the dike falls into a "failure zone" due to the combined effects of these uncertainties. Specifically, the probabilistic approach highlighted that the variability in environmental forces (wind speed and wave action) and soil properties can lead to an increased likelihood of failure.

In line with the study, the geotechnical report clearly shows pre-determined values and lacks actual results since there are few boreholes used for the geotechnical analysis of the soil where the dike was constructed. Although evidence of failure is prominent in the results of the study, further investigations should be made, especially with the soil parameters concerning the stability of the dike. Issues regarding the actual reports must be investigated to prevent loss of structural integrity on the part of the construction of dikes near bodies of water, since an increase in water pore pressure due to elevated water levels can affect the sliding failure, which in turn affects the dike [25].

7. ACKNOWLEDGMENTS

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