Seatific, Vol. 4, Issue. 2, pp. 77–87, December 2024

Seatific Journal
https://seatific.yildiz.edu.tr
DOI: https://doi.org/10.14744/seatific.2024.0009

Seatific

Review Article

Reliability analysis of the Porto Velho Pier - Rio Grande/RS through limit equilibrium and finite element method

Luiza Antiqueira da SILVA NETA*, Diego de Freitas FAGUNDES, Antônio Marcos de Lima ALVES

Department of Engineering, Federal University of Rio Grande, Rio Grande, Brasil

ARTICLE INFO

Article history
Received: October 30, 2024
Revised: December 13, 2024
Accepted: December 24, 2024

Key words:
Finite element method; Porto Velho pier in the city of Rio Grande - RS, seawall; stability analysis; reliability analysis; limit equilibrium method

ABSTRACT

This study analyzes the global stability of the Porto Velho pier, a structure in the port complex of the city of Rio Grande - RS, Brazil. This structure is a gravity pier with a length of 640 m which has been showing excessive displacements in a 150 m stretch. Limit Equilibrium and Finite Element tools associated with the Monte Carlo and FOSM Methods were applied. Four scenarios will be analyzed that represent the evolution of the erosion of the base of the pier structure, in which it can be concluded that as the loss of soil and rockfill of the base occurs, it presents a reduction in the safety factor and according to the FEM results in its rupture. In addition, the FEM analysis shows that the strength criterion of the pier's protective rockfill has a significant influence on the stability of the pier, since when it is considered to be linearly elastic, the structure behaves very similarly to that found by the LEM, while when the Mohr Coulomb criterion is adopted, the structure behaves in a way that is more representative of what is observed in situ.

Cite this article as: Silva Neta LA, Fagundes DF, Alves AML. Reliability analysis of the Porto Velho Pier - Rio Grande/RS through limit equilibrium and finite element method. Seatific 2024;4:2:77–87.

1. INTRODUCTION

In traditional deterministic analyzes of slope stability, uncertainties related to the problem are commonly neglected. A better understanding of these uncertainties, whether intrinsic or epistemic, has become an object of great interest in geotechnical research in the last two decades through the use of reliability analyzes to assess the probability of slope failure (Dyson and Tolooiyan 2019, Hostettler et al. 2019, Li et al. 2019).

According to Vanmarcke (1977), there are many uncertainties involved in slope engineering, especially with regard to the spatial variability of geotechnical properties and the uncertainties associated with deterministic calculations to estimate the safety margin of slope stability. The assessment of slope stability is affected as the variability of the soil affects the analysis systematically or randomly. Thus, geotechnical variability is complex, resulting from various sources of uncertainty, such as the mechanical and physical properties of soils and rocks, which are naturally dispersed, plus inaccuracies in transformation models and uncertainties related to human error (Phoon and Kulhawy 1999, Yang et al. 2020, Ansari et al. 2021).

System failure occurs when the slope slides along a critical surface. Thus, slope reliability analysis is defined as a system reliability analysis problem in which the overall failure probability (or system failure probability, Pf) of a slope, considering several potential sliding surfaces, is of interest and is greater than the failure probability of any individual potential sliding surface as a result of system effects (Diltlevsen 1979, Cho 2013, Zeng et al. 2015, Metya et al. 2017).

***Corresponding author.**
*E-mail address: antiqueiraneta@gmail.com

Several authors have been studying the use of reliability analysis. Haldar (2019) presents an overview of foundation design methodologies highlighting methodologies such as FORM (First Order Reliability Method) and the Monte Carlo method. The author highlights the importance of foundation designs based on reliability, then considering the variability and spatial correlation of the soil, leading to rational design decisions.

Beloni et al. (2017) analyzed the geotechnical reliability of the pile foundation of a port pier located in the city of Rio Grande, RS. In their study, the probabilistic distribution of the bearing capacity was assessed using Bayesian theory concepts. The authors also emphasized the importance of reliability studies for accurately evaluating the safety of any engineering project.

In 2000, the Porto Velho pier, in Rio Grande/RS (Fig. 1), began to show excessive displacements towards the channel and the formation of cracks in the sidewalk, possibly related to the rupture of the structure (Fig. 2). The objective of this work is, therefore, to analyze the stability of the Porto Velho pier through a reliability analysis, as well as to infer the evolution of the safety factor as an erosion process occurs at the base of the pier structure. The stability analysis will consist of using two approaches, the limit equilibrium method (LEM) and the finite element method (FEM). From these, a reliability analysis will be carried out using the Monte Carlo method (MMC) and the first order first moment method (FOSM). This study will enable the understanding of the development of port structures' stability, thus providing a basis for decision-making regarding future mitigation projects for the pathological manifestations observed along the structure. Furthermore, the study may also contribute to future investigations on stability analysis, using reliability methods in gravity-type port structures.

2. MATERIALS AND METHODS

2.1. Deterministic method

The most common techniques for slope stability analysis are deterministic. These techniques assume the constancy of the variables used in the calculation model. This methodology usually uses the Limit Equilibrium Method (LEM) to determine the minimum safety factor for the slope failure surface (Ortigão and Sayão, 2004). According to Cho (2010), slope stability problems are commonly analyzed using the LEM. The failing soil mass is divided into a number of vertical layers (slices) to calculate the factor of safety, which is defined as the ratio of the shear strength stresses to the mobilized shear stresses, so the static equilibrium between the slices and the mass as a whole are used to solve the stability problem. However, all slice methods are statically indeterminate and, as a result, require assumptions to solve the problem. Furthermore, LEM does not consider the stress-strain behavior of the materials involved in the analysis.

Another technique for slope stability analysis is the Finite Element Method (FEM). According to Zaman et al. (2000) the FEM represents a powerful alternative approach to slope stability analysis. This method is accurate, versatile and requires fewer a priori assumptions, especially regarding the failure mechanism. In this method, the changing stress-strain condition in the soil is considered, thus focusing mainly on the failure mechanism during a slope failure (Duncan, 2014).

According to Griffiths and Lane (1999), in this method the shear strength parameters of the soil c' and tan ϕ' are reduced by a Strength Reduction Factor (SRF) until failure occurs (Equation 1). In this study, PLAXIS 2D (2016) software was used for stability analysis. It is understood that the value of the safety factor is the same as the value of the SFR at the time of failure.

$$\mathrm{SRF} = \frac{\tan(\emptyset')}{\tan(\emptyset'_{reduced})} = \frac{C'}{C'_{reduced}} \tag{1}$$

2.2. Probabilistic method

Probabilistic procedures for slope stability analysis vary in their assumptions, limitations, ability to deal with complex problems and mathematical complexity. Most of them, however, fall into one of two categories: approximate methods (First Order Second Moment Method, Point Estimation Method) and Monte Carlo Simulation (El-Ramly, 2002).

According to Da Re et al. (2001), reliability analysis provides a systematic method for evaluating the combined influences of uncertainties in the parameters that affect the factor of safety. Thus, probabilistic analysis evaluates the stability conditions of slopes, taking into account the errors associated with the nature of the problem and the variability of the characteristics of the slope and its soil. Through this analysis, the safety of a slope is characterized by the value of the safety factor (FS) based on average values corrected for probabilistic parameters, or by the value of the reliability index (β), which implicitly involves the behavior of a function of random parameters, which defines the state of safety of a slope.

Thus, the reliability index describes the stability of the slope by the number of standard deviations separating the average factor of safety from its failure value, which is defined as 1. The reliability index can also be defined as a way of normalizing the factor of safety in relation to its uncertainty. Equation 2 shows the calculation for determining the reliability index (Abbaszadeh et al. 2011).

$$\beta = \frac{E[FS] - 1}{\sigma[FS]} \tag{2}$$

Where β represents the reliability index, E[FS] the expected value of the safety factor and σ[FS] the standard deviation of the factor of safety. Table 1 illustrates the relationship between the reliability index and the probability of failure, assuming a normal distribution for the safety factor.

The variability of the parameters is given as a function of the coefficient of variation (COV). Duncan et al. (2014) defines the COV as the ratio between the standard deviation (σ) and the arithmetic mean (μ) of a sample, so this parameter designates the dispersion of the data in relation to the mean, and its result is expressed as a percentage (Eq. 3).

$$COV = \frac{\sigma}{\mu} * 100 \tag{3}$$

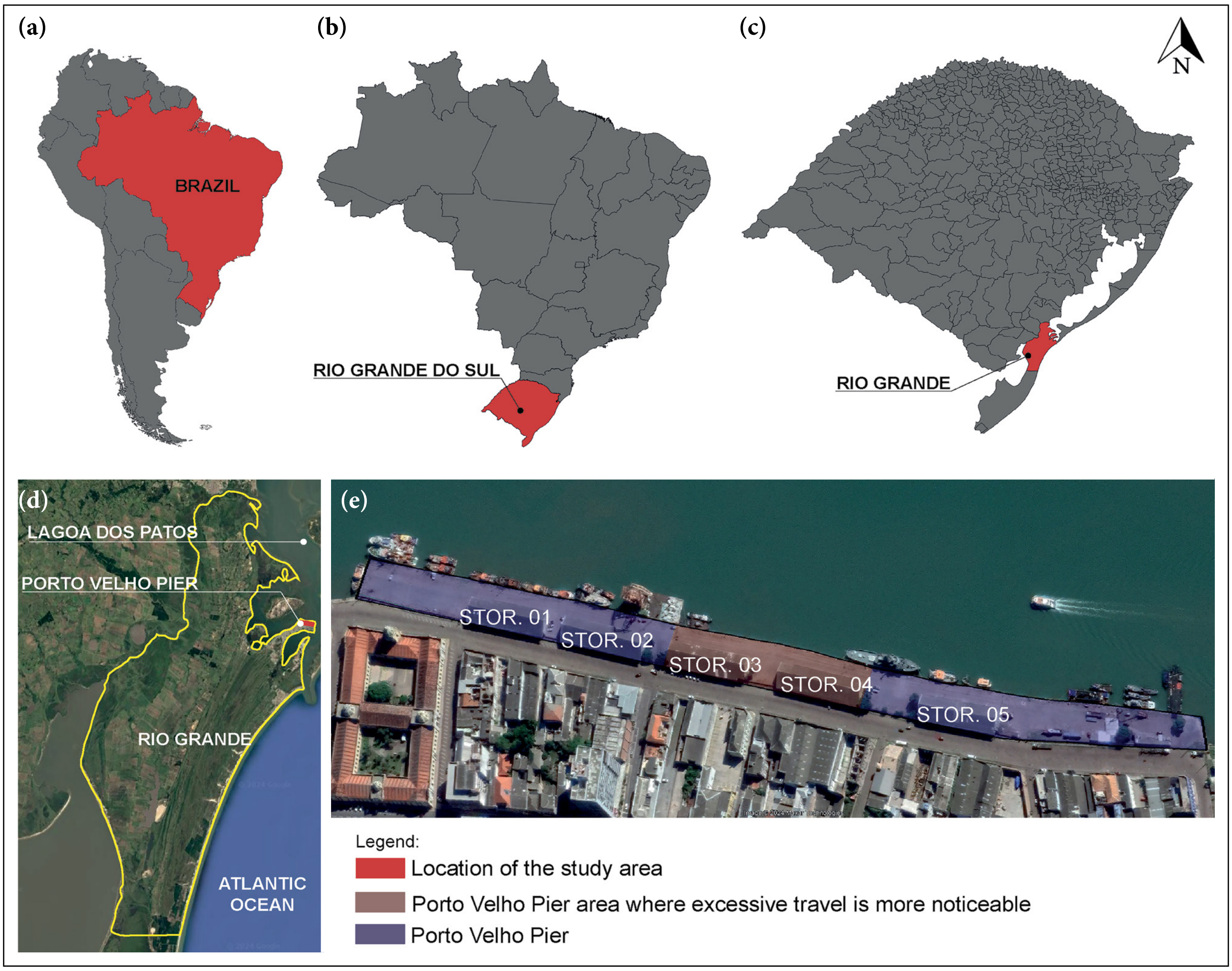

Figure 1. (a) Continental, state and municipal identification of the studied location; (b) Location of the Porto Velho Pier in the municipality of Rio Grande; (c) Identification of the study area.

In the Monte Carlo Method (MMC), the stability of the structure is calculated by generating a large number of random data for the input variables (such as friction angle and cohesion), since the probability distribution of these variables is known. As the data is generated, stability is analyzed using deterministic methods, which also makes it possible to determine the measures of central tendency corresponding to the factor of safety, as well as the corresponding probability of failure (Cho, 2010).

There are two important aspects to MMC. The first refers to the search for the critical surface for each set of randomly generated input data values, which involves significant computational effort, making it impractical. The way commonly used to resolve this difficulty is to take as the critical rupture surface the one obtained by the deterministic method, which is therefore independent of the values of the probabilistic analysis input data set (El Ramly, 2001).

According to Li et al. (2013) the probability of system failure ($P_{f,s}$) is frequently calculated using a large, but finite, number of potential sliding surfaces. Let S_1, S_2, ..., S_{Ns} denote N_s potential slip surfaces that are considered in the limit equilibrium analysis of slope stability. Then, the slope can be considered as a series system consisting of N_s components (i.e. S_1, S_2, ..., S_{Ns}). System failure occurs when any component (i.e. S_1, S_2, ..., S_{Ns}) fails. The probability of system failure ($P_{f,s}$) can be calculated using Equation 4.

$$P_{f,s} = \frac{1}{N_t} * \sum_{k=1}^{N_t} I(FS_{mim} < 1) \tag{4}$$

Where N_t is the total number of simulations generated during the MCS; FS_{min} is the minimum safety factor value among the safety factor values for the N_s potential slip surfaces for a given set of random samples of uncertain parameters X (i.e., c_u, c and ∅) involved in the slope stability analysis; and $I\{.\}$ is the function indicator. For a given random sample $I(FS_{min}<1)$ is taken as a value of 1 when $FS_{min}<1$ occurs. Otherwise, it is equal to zero.

The slip surface with FS_{min} (i.e. critical slip surface) needs to be located between potential slip surfaces for each sample generated during MCS, and its correspondent is calculated using a deterministic slope stability analysis method, such as limit equilibrium methods (Duncan et al. 2014).

The First-Order, Second Moment (FOSM) method is based on truncating the Taylor Series expansion function. According to Griffith (2007), this method provides analytical

Figure 2. (a) Displacement of the pier structure blocks. (b) Height variation along the pavement and pier crown blocks. (c) Displacement of the gravity wall towards the navigation channel. (d) Area where displacements are most intense.

approximations for the mean and standard deviation of a parameter of interest, as a function of the mean and standard deviation of the various input factors, and their correlations.

Thus, the calculation is based on the variation in the FS caused by a small oscillation in the independent variables. The number of analyses required for this procedure is equal to n+1, where n is the number of independent values. Equation 5 shows this process.

$$V[FS] = \sum_{i=0}^{n} \left(\frac{\delta FS_{ii}}{\delta X_{ii}}\right)^2 * V[X_i] \quad (5)$$

Where $V[FS]$ equals the variance of the FS, δFS_{ii} corresponds to the variance of the *FS* when the study variables are varied by δX_i and $V[X_i]$ means the variance of each of the variables (X_i).

2.3. Stability analysis using SLIDE 6.0 Software

The SLIDE 6.0 software uses LEM for global stability analysis, which can be either deterministic or probabilistic. The probabilistic analysis is carried out by applying the Monte Carlo method, so in order to optimize the computational demand, the software allows this analysis to be carried out in two ways, the Global Minimum and the Overall Slope.

In the Global Minimum type analysis, parameter variability is applied only to the critical rupture surface, while the Overall Slope analysis considers parameter variation for all rupture surfaces. This study will therefore focus on analyzing the Overall Slope analysis only.

Stability analysis using the FOSM method was carried out using SLIDE 6.0 and Excel software. First, deterministic analyses were carried out for each of the parameter variations required by the method and then the equations were used in Excel. Based on this methodology, it is possible to identify which parameters have the greatest influence on the safety factor.

2.4. Stability analysis using PLAXIS 2D software

The analysis was carried out using PLAXIS 2D software, where, and the Safety Factors for each of the scenarios studied were calculated using the Finite Element Method. To do this,

Table 1. Expected performance level according to reliability index values and probability of failure

Expected performance level	Reliability index (β)	Probability of failure (Pf)
High	5.0	0.0000003
Good	4.0	0.00003
Above average	3.0	0.001
Below average	2.5	0.006
Poor	2.0	0.023
Unsatisfactory	1.5	0.07
Dangerous	1.0	0.16

Source: Adapted from U.S. Army Corps Engineers (1995).

a mesh study was first carried out. The main objective of this study is to identify the most optimized analysis model, i.e. the model that requires the least possible computational effort in order to provide the most assertive results possible.

To generate the finite element mesh, it is necessary to divide the domain into several parts. For two-dimensional analysis, several triangles are generated to represent the simulation domain. In the general properties of PLAXIS 2D, the number of nodes to be analyzed per element triangle is defined. Where there is the option of using an analysis with 6 or 15 nodes per element, in this study the use of 15 nodes was adopted.

Subsequently, the analysis began, in which it was identified that the fine and very fine meshes are the ones with the most assertive results. Table 2 shows the results of the mesh analysis. It can be seen that although the very coarse mesh does not show convergence on the safety factor, the difference between the result obtained by the very coarse mesh and the very fine mesh is less than 1%. Based on this analysis, it was decided to carry out all the analyses with the very fine mesh.

Therefore, the modeling steps consisted of importing the cross section of the pier, as well as its geotechnical profile. Subsequently, the geotechnical parameters involved in the analysis were defined, as well as the boundary conditions, such as the water table level, for example. After defining the input data and generating the mesh. The construction stages of the model were defined, where phase 1 consisted of determining the initial stress field in the soil through the "k0 procedure". The phase consists of the insertion of the pier structure, as well as the backfilling of the back area. In phase 3, the service and mooring loads are inserted, in this step the analysis of scenarios 1 and 2 is carried out. Subsequently, in phases 4 and 5, respectively, the analysis of the structure begins as a function of the erosive process at the base of the wall. Thus, characterizing scenarios 3 and 4 respectively.

3. GEOTECHNICAL CONDITIONS AND SCENARIOS ANALYZED

Through a historical search of the Port of Rio Grande's technical archives, in addition to the project for the structure of the Porto Velho Pier, 12 SPT test tests were found, all of them of the Standard Penetration Test (SPT) type. Figure 3 shows the location of each of the tests. As mooring bollards 13 is the place where the pathological manifestations are most intense, it can be seen that this is also the place where there are the greatest number of tests. An analysis of the SPT test reports shows that they are very similar. When analyzing the SP1, SP1A and SP1B tests, it can be seen that they all have a layer of approximately 3m of sand where the SPT test is interrupted, once it reaches an impenetrable layer, because at these points where the test was carried out there is the rockfill structure at the end of the pier. Already the SP1C test goes into deeper layers, in this report it is possible to identify the other soil layers of the site, Figure 4 shows the result of the SP1B sounding report, which is similar to the SP1 and SP1A reports, and SP1C. Based on these tests, the geotechnical profile of the site was defined.

Table 2. FEM mesh analysis

Mesh type	Number of elements	FS
Very thick	5351	1.658
Thick	6665	1.656
Average	7787	1.649
Thin	10279	1.644
Very fine	14057	1.644

FEM: Finite element method; FS: Safety factor.

By applying empirical equations that correlate the NSPT number with its properties, the average geotechnical parameters of the soil that makes up the Pier structure were defined. The rockfill parameters were the same as those used in the studies by Meirelles (2008).

Therefore, for this study, a high variability of the geotechnical parameters will be considered, since previous studies have already analyzed how the COV influences the stability of the structure, where it was possible to observe that higher COVs present a greater probability of failure and lower reliability rates. Therefore, the standard deviations of each of the geotechnical parameters were calculated based on the definition of the coefficient of variation (Eq. 3). Table 3 illustrates the values adopted for each of the parameters according to the analyses carried out. It was possible to define the layout of the structure by reviewing the history of the works and the quay project. By overlaying this information with the results of the SPT tests, the cross-section of the Porto Velho pier was defined.

According to Lacasse and Nadim (1998), most geological processes follow a normal or lognormal probabilistic distribution. A normal distribution was adopted for the random variables, in this case, the soil resistance parameters (undrained resistance and friction angle) as well as the specific weight. The other parameters were treated as deterministic, as in Johari (2019) (Table 4).

Thus, an analysis of four scenarios is proposed, in which scenario 1 represents the original undamaged structure, considering only the variability of the soil and its respective parameters, and the rockfill protection soil is characterized

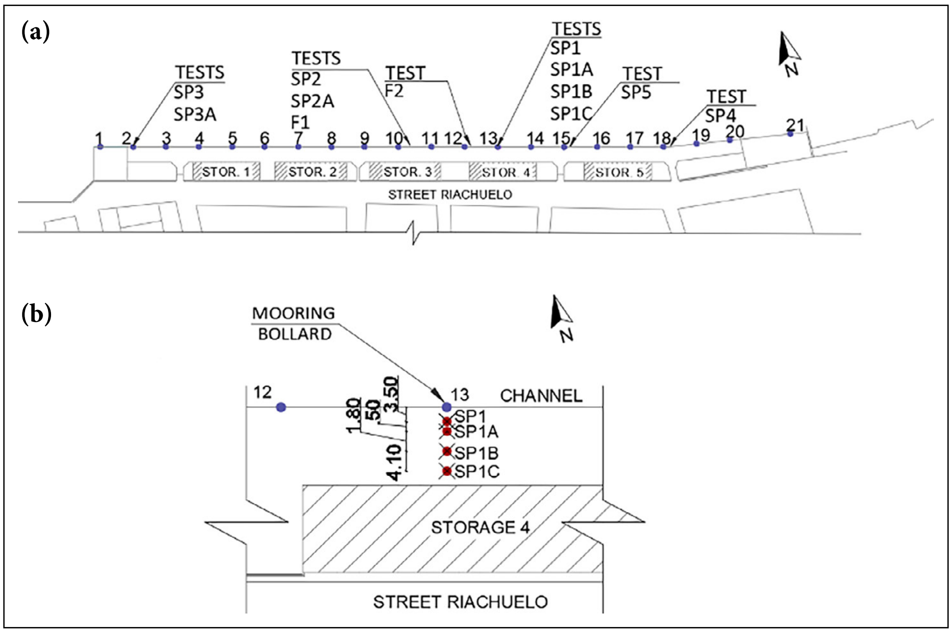

Figure 3. Geotechnical investigation (a) locations of the SPT test along the pier; (b) Identification of boreholes in front of mooring bollard 13.

SPT: Standard Penetration Test.

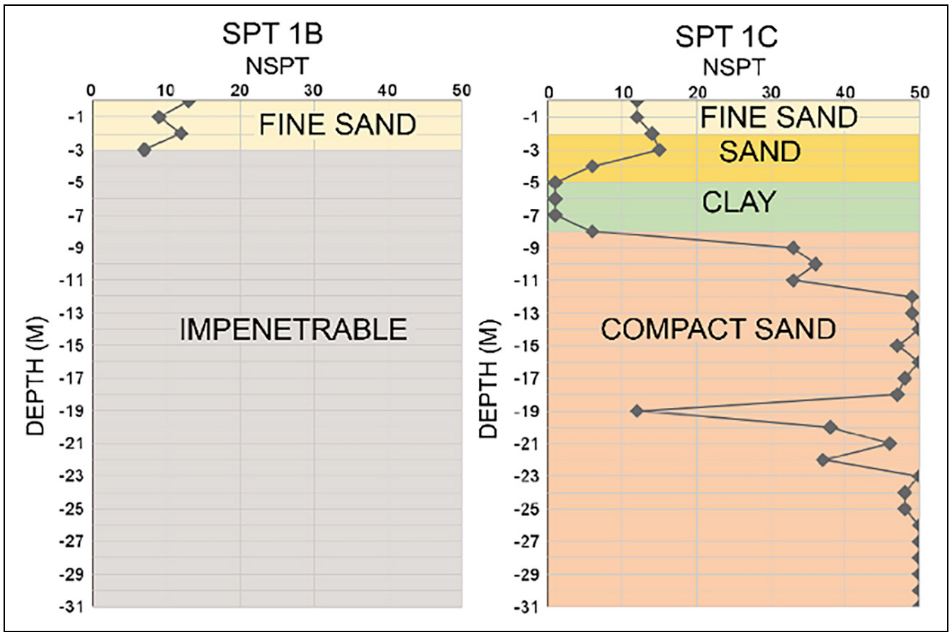

Figure 4. Results of the soil profile of the tests SP1B and SP1C, carried out in front of mooring bollards 13.

as compact sand. In order to understand how the rockfill protection soil influences the stability of the structure, it was considered that this soil is clay, so this new scenario was assigned as scenario 2.

As observed in a diving survey carried out by SUPRG (2016), there was erosion at the base of the rockfill protecting the wall, so this situation was defined as scenario 3 for this study. Finally, scenario 4 is represented as an evolution of scenario 3, in which erosion of part of the quay's protective rockfill is observed. Figure 5 illustrates the section of the quay for the different scenarios analyzed.

After defining the soil parameters, the structure was modeled using SLIDE 6.0 and PLAXIS 2D software (Fig. 6). In the PLAXIS 2D software, the continuum was discretized into a mesh with 1726 ground elements 1726, 14286 nodes, the average size of the elements 2,139 m, maximum element size 4.694m and minimum element size 0.0448m. The dimensions of the structure were defined based on old projects found in the SUPRG technical collection. It is important to highlight that the dimensions of the structure remained the same for both the LEM and FEM analyses.

Table 3. Geotechnical parameters for the LEM

Monte Carlo soil					FOSM		
	Parameters	Average	COV (%)	Standard deviation	Relative minimum	Relative maximum	Average +10% variation
Soil 1: Fine sand	γ (kN/m³)	19	10	1.9	13.3	24.7	20.9
	∅ (°)	35	15	5.25	19.25	50.75	38.5
Soil 2: Sand	γ (kN/m³)	18	10	1.8	12.6	23.4	19.8
	∅ (°)	29	15	4.35	15.95	42.05	31.9
Soil 3: Clay	γ (kN/m³)	15	10	1.5	10.5	19.5	16.5
	Su (kPa)	25	30	7.5	2.5	47.5	27.5
Soil 4: Compact sand	γ (kN/m³)	20	10	2	14	26	22
	∅ (°)	35	15	5.25	19.25	50.75	38.5
Soil 5: Filter (sand)	γ (kN/m³)	18	10	1.8	12.6	23.4	19.8
	∅ (°)	29	15	4.35	15.95	42.05	31.9
Rockfill	γ (kN/m³)	30					
	∅ (°)	45					

LEM: Limit equilibrium method; FOSM: First order first moment method; COV: Coefficient of variation.

Table 4. Geotechnical parameters for the FEM

Material	Average parameter values				
	Specific weight (kN/m³)	Angle of friction (°)	Non-drained resistance (Kpa)	Modulus of elasticity (kPa)	Poisson's coefficient
Soil 1: Fine sand	19	35	-	2.00E+04	0.3
Soil 2: Sand	18	29	-	1.50E+04	0.3
Soil 3: Clay	15	-	25	7000	0.4
Soil 4: Compact sand	20	35	-	5.00E+04	0.35
Soil 5: Filter (unidentified material)	18	29	-	1.50E+04	0.3
Rockfill	30	45		1.56E+05	0.3

FEM: Finite element method.

4. RESULTS AND DISCUSSIONS

4.1. Probabilistic analysis

Table 5 shows the evolution of the safety factor for each of the scenarios analyzed. It can be seen that scenario 1 had a safety factor greater than 2, very low failure probabilities and high reliability indices, and the same can be seen for scenario 2. As the analyses move on to scenarios 3 and 4, it can be seen that the safety factor values are lower than 2 and higher than 1.8, with a low probability of failure and a reliability index close to 3, which according to Table 1, characterizes an above-average reliability index. Thus, it can be seen that the safety factor decreases by 20% when the base of the rockfill is lost. It can also be seen that the value of the safety factor according to the probabilistic analysis is higher than the values found in the deterministic analysis, because the probabilistic analysis takes into account the variability of the materials.

In order to understand how soil variability influences the safety factors found by the FEM, a probabilistic analysis was carried out. It is important to emphasize that this analysis was based on the safety factors calculated using the Mohr-Coulomb rockfill resistance criterion.

4.2. Finite element method

It should be noted that throughout the analysis, it was noticed that the values of the safety factors found were lower than the values of the safety factors found by the Limit Equilibrium Method. In order to understand the reason for this difference, a series of changes were made to the input parameters in order to identify which properties would significantly affect the safety factor:

- Insertion of soil-structure interaction interfaces;
- Exponential increase in modulus of elasticity;
- Updating the mesh at each new analysis stage;
- Removal of distributed and point loads;
- Change in the rockfill resistance criterion from Mohr Coulomb to Linear Elastic;

In view of all these changes, the only one that had a significant impact was the change in the rupture criterion. Table 6 shows a comparison of the safety factor values found considering the rockfill failure criterion as Mohr-Coulomb and Linear Elastic for the FEM. The table also shows the results of the deterministic LEM analysis. Figure 7 shows the failure surfaces of Scenarios 1, 2,3

Seatific, Vol. 4, Issue. 2, pp. 77–87, December 2024

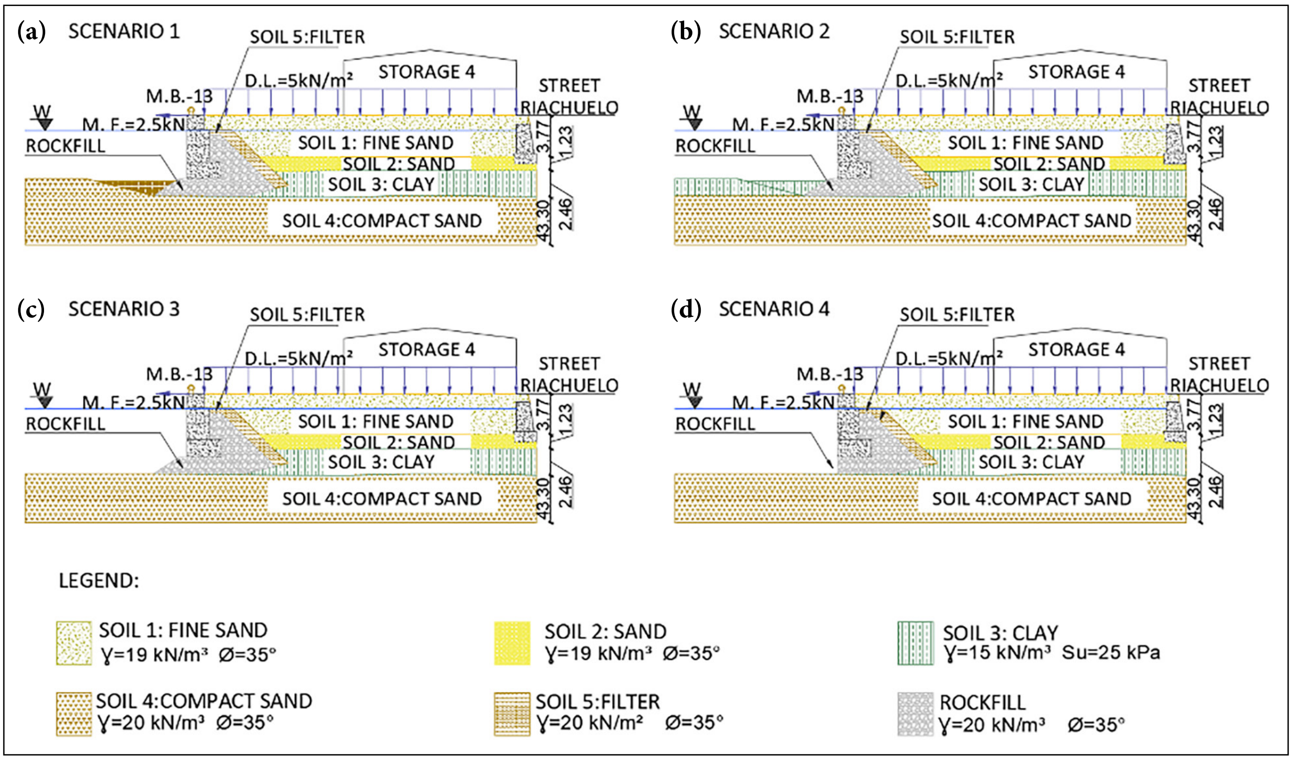

Figure 5. (a) Scenario 1: Sandy soil at the base of the rockfill protection. (b) Scenario 2: Clayey soil at the rockfill protection base. (c) Scenario 3: Intermediate erosion process with loss of soil protecting the rockfill. (d) Scenario 4: Critical stage where erosion of the rockfill at the base of the structure occurs.

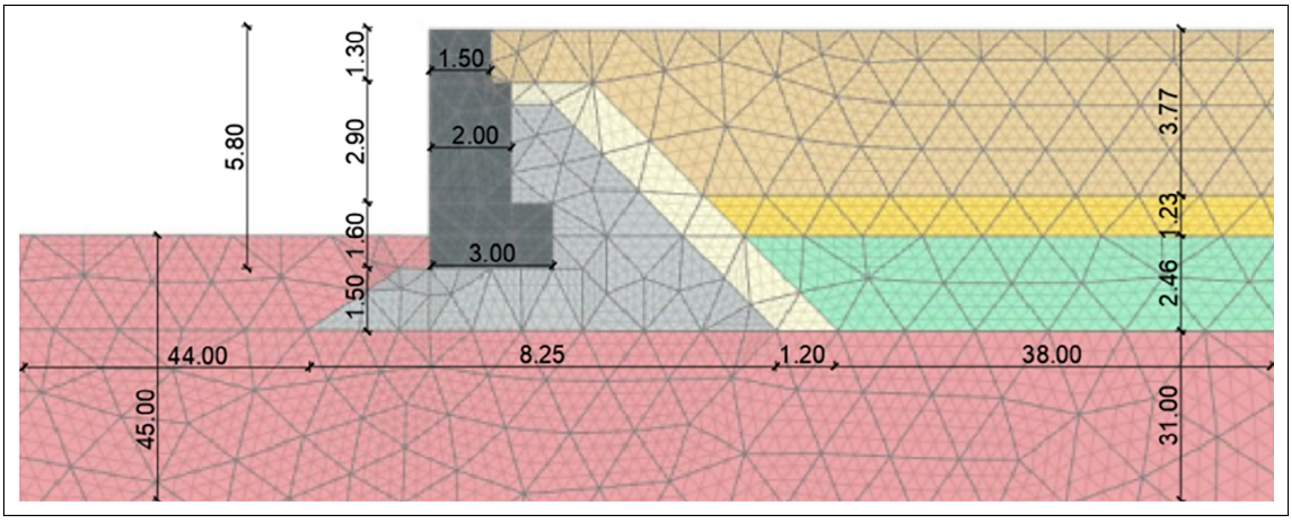

Figure 6. Dimensions of the PLAXIS 2D software model, the continuum was discretized into 1726 triangular elements with 15 nodes.

and 4 using the Limit Equilibrium Method and the Finite Element Method, respectively.

Based on these results, it can be understood that LEM is based on the premise that the safety factor is defined on the basis of the balance between the stresses and the stresses developed during the analysis. The FEM, on the other hand, considers the integration between the elements of the structure, so that they respond directly to the stress-strain relationship. Therefore, by adopting a linear elastic strength criterion for the rockfill, it is possible to see that the system behaves in a very similar way to that found in the FEM analysis, since the linear elastic strength criterion gives the rockfill a very high rigidity, similar to what is reproduced in the SLIDE software, where the FEM analysis is carried out, in which the modulus of deformation of the materials is not taken into account, as well as the interaction between them.

This analysis can be seen by comparing the results of the safety factors between the LEM and the FEM (Linear Elastic). It can be seen that the values are very close, and Figure 7 shows the rupture zones of the structure. It can be seen that the critical rupture surface of the LEM is very close to the plasticization zone of the FEM using the Linear Elastic model.

Table 5. Stability analysis results for LEM

Method	Scenario 01			Scenario 02			Scenario 03			Scenario 04		
	$\overline{FS}$	P_f	β	$\overline{FS}$	P_f	β	$\overline{FS}$	P_f	β	$\overline{FS}$	P_f	β
DET	2.204	-	-	2.289	-	-	1.845	-	-	1.778		
MMC	2.46	1.00E-05	4.261	2.365	2.00E-05	4.046	1.985	4.00E-04	3.345	1.93	5.00E-04	3.3
FOSM	2.348	9.00E-06	4.281	2.289	2.00E-06	4.567	1.915	3.00E-05	4.029	1.849	2.00E-04	3.54

LEM: Limit equilibrium method; DET: Deterministic; MMC: Monte Carlo method; FOSM: First order first moment method.

Table 6. Comparison of the results of safety factors for LEM and FEM

Scenarios	FEM		LEM
	Mohr coulomb	Linear elastic	Morgenstern & price
1	1.646	2.903	2.204
2	1.604	2.647	2.289
3	1.071	2.005	1.84
4	-	1.538	1.778

LEM: Limit equilibrium method; FEM: Finite element method.

By adopting the Mohr-Coulomb strength criterion for the rockfill, there is a significant reduction in the safety factor. This is because in this analysis, the rockfill has a more realistic resistance criterion, so that the load related to the mooring effort causes a stress-strain relationship that has a direct impact on the value of the safety factor, which does not occur in the LEM analysis.

It is therefore understood that the PLAXIS 2D software satisfactorily reproduces the stability analysis of the structure so that when similar analysis criteria are inferred, the results found are very close to those calculated using the SLIDE software. However, it should be noted that the analysis methodologies are very different, so that when a more realistic failure criterion is applied to the structure, the analysis results in safety factors that are lower than those calculated by LEM. This is because the FEM considers a wider range of parameters in its analysis. In addition, this method also takes into account the horizontal forces acting on the structure, which LEM does not.

Table 7. Results of the FOSM method for the FEM

Scenario	Analysis method	$\overline{FS}$	P_f	β
1		1,646	8E-05	4,175
2	Phi/c-reduction	1,604	6E-06	4,392
3		1,071	7E-05	3,799

FEM: Finite element method; FOSM: First order first moment method.

In order to understand how the variability of the soil influences the safety factors found by the FEM, a probabilistic analysis was carried out. It is important to emphasize that this analysis was based on the safety factors calculated using the Mohr-Coulomb rockfill resistance criterion.

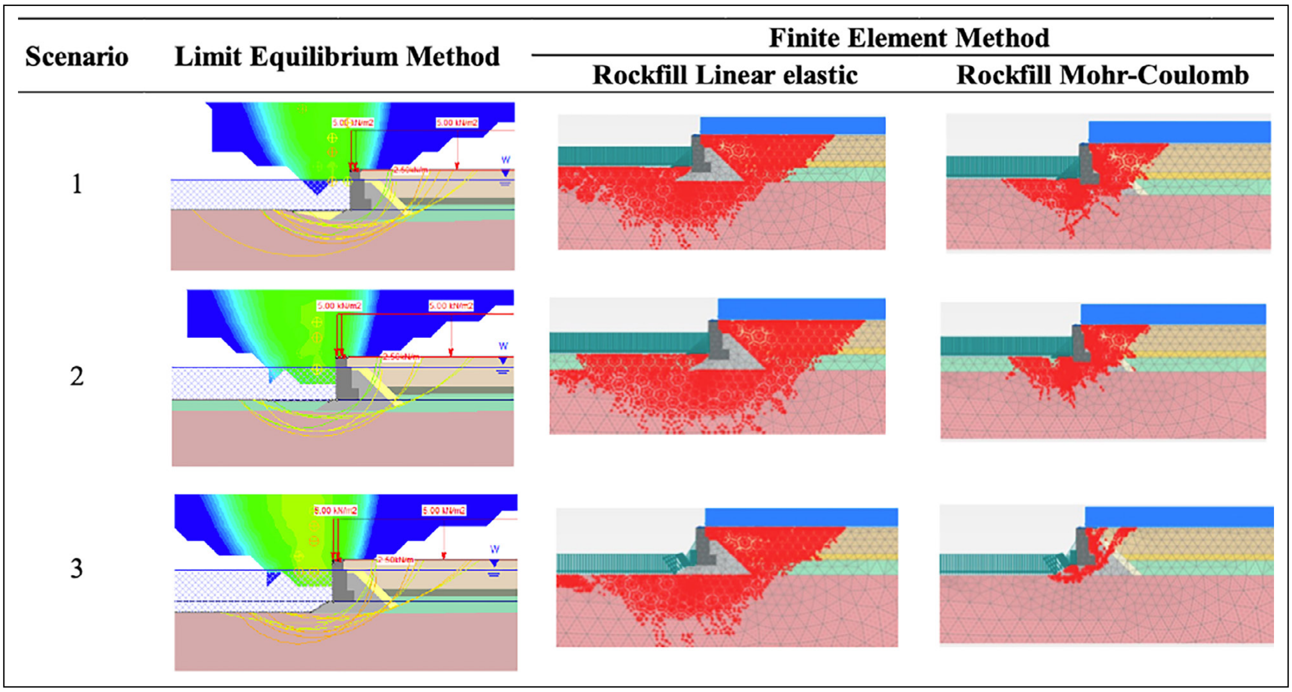

Figure 7. Comparison of the rupture surfaces of the LEM and FEM.

LEM: Limit equilibrium method; FEM: Finite element method.

Table 7 shows the results of the FOSM analysis. It shows that the factor of safety is lower than the factor of safety found in the FOSM method for the LEM. However, for both analyses it is possible to see that as the variability of the geotechnical parameters is applied, there is a reduction in the reliability index. When relating the results of Figure 7 to the results of the FOSM analysis for the LEM, it can be seen that the reliability index is very similar to that found by the LEM.

It is important to highlight that even though the FEM results in lower safety factors than those found by the LEM, the structure's reliability index continues to present an above-average level of performance. Therefore, it is understood that as erosion of the base of the structure occurs, its reliability reduces.

6. CONCLUSION

From this study it is possible to understand how the stability of the Porto Velho pier is influenced by the variability of the geotechnical parameters, as well as the probability of failure of each of the scenarios analyzed. In addition, it was possible to see the evolution of the safety factor as the loss of the quay base structure occurs.

By applying the probability analyses for the Limit Equilibrium Method, it was possible to notice a convergence between the results found for the Monte Carlo and FOSM methods.

The Finite Element Method analysis showed that adopting the rockfill strength criterion as Linear Elastic resulted in a plasticization area very similar to the areas of the critical rupture surfaces found in the Limit Equilibrium Method, as well as having very close safety factor values. However, by adopting the rockfill resistance criterion as being Mohr Coulomb, the safety factors showed much lower values than those calculated by the Limit Equilibrium Method. With regard to Scenario 4, the FEM identified the rupture of the structure at this stage.

In view of the above, it can be seen that the variability of the parameters directly influences the probability of failure of the structure as well as its reliability index. Furthermore, it can be understood that the stability of the Porto Velho pier is influenced both by the loss of the protective soil at the base of the rockfill and by the erosion of the rockfill base itself.

This research showed that for the configuration of the Porto Velho pier section, the Finite Element Method presented more assertive results when compared to the results inferred by the Limit Equilibrium Method. This is because the FEM takes into account the interaction between the elements as well as their stiffness. Through the analyses carried out and the results presented, it was identified that the rockfill strength criterion has a major influence on the safety factor.

In addition, the FEM identified the rupture of the quay structure from the moment the base of the rockfill was lost. This conformation is also observed in the existing structure of the Porto Velho pier. Therefore, it is assumed that the deformations found at the site stem from the loss of the rockfill base.

ACKNOWLEDGEMENTS

The Federal University of Rio Grande and the Port of Rio Grande for sharing their technical assets to enable this research to be carried out.

DATA AVAILABILITY STATEMENT

The published publication includes all graphics and data collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

USE OF AI FOR WRITING ASSISTANCE

No AI technologies utilized.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

REFERENCES

Abbaszadeh, M., Shahriar, K., Sharifzadeh, M., & Heydari, M. (2011). Uncertainty and reliability analysis applied to slope stability: A case study from Sungun copper mine. *Geotechnical and Geological Engineering, 29*(5), 581–596. [CrossRef]

Ansari, T., Kainthola, A., Singh, K. H., Singh, T. N., & Sazid, M. (2021). *Geotechnical and micro-structural characteristics of phyllite-derived soil: Implications for slope stability*. Lesser Himalaya, Uttarakhand, India. Catena, 196, 104906. [CrossRef]

Beloni, A. V., Alves, A. M. L., & Real, M. V. (2017). Análise de confiabilidade das estacas do cais do Porto Novo de Rio Grande (Brasil) empregando metodologia bayesiana. *Geotecnia, 141*, 19–39. [CrossRef]

Cho, S. E. (2013). First-order reliability analysis of slope considering multiple failure modes. *Engineering Geology, 154*, 98–105. [CrossRef]

Cho, S. E. (2010). Probabilistic assessment of slope stability that considers the spatial variability of soil properties. *Journal of Geotechnical and Geoenvironmental Engineering, 136*(7), 975–984. [CrossRef]

Christian, J., Ladd, C., & Baecher, G. (1994). Reliability applied to slope stability analysis. *Journal of Geotechnical Engineering, 120*(12), 2180–2207. [CrossRef]

Corps of Engineers. (1997). *Engineering and design introduction to probability and reliability methods for use in geotechnical engineering*. Engineering Technical Letter No. 1110-2-547. Department of the Army, U.S., Washington, DC.

Da Re, G., Germaine, J. T., & Ladd, C. C. (2001). *Physical mechanisms controlling the pre-failure stress-strain* *behavior of frozen sand*. Massachusetts Institute of Technology, Department of Civil and Environmental Engineering.

Ditlevsen, O. (1979). Narrow reliability bounds for structural systems. *Journal of Structural Mechanics, 7*(4), 453–472. [CrossRef]

Duncan, J. M., & Wright, S. G. (2014). *Soil strength and slope stability*. Wiley.

Dyson, A. P., & Tolooiyan, A. (2019). Probabilistic investigation of RFEM topologies for slope stability analysis. *Computers and Geotechnics, 114*, Article 103129. [CrossRef]

El-Ramly, H. (2001). *Probabilistic analyses of landslide hazards and risks: Bridging theory and practice* [Doctorial thesis]. University of Alberta, Canada.

Griffiths, D. V., & Lane, P. A. (1999). Slope stability analysis by finite elements. *Geotechnique, 49*(3), 387–403. [CrossRef]

Griffiths, D. V., & Fenton, G. A. (2007). Probabilistic methods in geotechnical engineering. In *International Center for Mechanical Sciences* (pp. 71–112). Springer. [CrossRef]

Haldar, S. (2019). Reliability-based design of pile foundations. In K. Ilamparuthi & G. R. Robinson (Eds.), *Geotechnical design and practice* (pp. 225–236). Springer. [CrossRef]

Hostettler, S., Jöhr, A., Montes, C., & D'Acunzi, A. (2019). Community-based landslide risk reduction: A review of a Red Cross soil bioengineering for resilience program in Honduras. *Landslides, 16*(9), 1779–1791. [CrossRef]

Jiang, S., Huang, J., Griffiths, D. V., & Deng, Z. (2022). Advances in reliability and risk analyses of slopes in spatially variable soils: A state-of-the-art review. *Computers and Geotechnics, 141*, Article 104498. [CrossRef]

Johari, A., & Mousavi, S. (2019). An analytical probabilistic analysis of slopes based on limit equilibrium methods. *Bulletin of Engineering Geology and the Environment, 78*, 4333–4347. [CrossRef]

Lacasse, S., & Nadim, F. (1998). *Risk and reliability in geotechnical engineering*. Proceedings of the 4th International Conference on Case Histories in Geotechnical Engineering, 1172–1192.

Li, D. Q., Wang, L., Cao, Z. J., & Qi, X. H. (2019). Reliability analysis of unsaturated slope stability considering SWCC model selection and parameter uncertainties. *Engineering Geology, 260*, Article 105207. [CrossRef]

Li, L., Wang, Y., Cao, Z., & Chu, X. (2013). Risk de-aggregation and system reliability analysis of slope stability using representative slip surfaces. *Computers and Geotechnics, 53*, 95–105. [CrossRef]

Meirelles, M. C. (2008). *Determination of the rockfill shear strength of the Machadinho HPP through large-scale direct shear tests* [Master thesis]. Federal University of Santa Catarina.

Metya, S., Mukhopadhyay, T., Adhikari, S., & Bhattacharya, G. (2017). System reliability analysis of soil slopes with general slip surfaces using multivariate adaptive regression splines. *Computers and Geotechnics, 87*, 212–228. [CrossRef]

Ortigão, J. A. R., & Sayão, A. S. F. J. (2004). *Handbook of slope stabilization*. Springer-Verlag.

Phoon, K. K., & Kulhawy, F. H. (1999). Characterization of geotechnical variability. *Canadian Geotechnical Journal, 36*(4) [CrossRef]

Plaxis 2D. (2016). *Plaxisbv*. Delft, Netherlands.

Queiroz, I. M. (2016). Comparison between deterministic and probabilistic stability analysis, featuring a consequent risk assessment. In: S. Aversa, L. Cascini, L. Picarelli, & C. Scaiva (Eds.), *Landslides and engineered slopes. Experience, theory and practice*. CRC Press.

SUPRG Technical Collection. (2016). *Inspection report on pathological manifestations along the Porto Velho Quay structure*.

Vanmarcke, E. H. (1977). Probabilistic modeling of soil profiles. *Journal of Geotechnical Engineering, 103*(11), 1227–1246. [CrossRef]

Yang, J., Dai, J., Yao, C., Jiang, S., Zhou, C., & Jiang, Q. (2020). Estimation of rock mass properties in excavation damage zones of rock slopes based on the Hoek-Brown criterion and acoustic testing. *International Journal of Rock Mechanics and Mining Sciences, 126*, Article 104192. [CrossRef]

Zaman, M., Booker, J. R., & Gioda, G. (2000). *Modeling in geomechanics*. John Wiley & Sons.

Zeng, P., Jimenez, R., & Jurado-Piña, R. (2015). System reliability analysis of layered soil slopes using fully specified slip surfaces and genetic algorithms. *Engineering Geology, 193*, 106–117. [CrossRef]