Deterministic and Probabilistic Approach in Slope Stability of a Tropical Soil

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***Abstract*—The stability of natural slopes in tropical regions is subject to erodibility due to the high periods of drought and rainfall. Thus, slope stability analysis is of great value for places subject to erosion. In addition, consideration of the dispersion of soil parameters used in stability calculations is important for a complete understanding of the failure probability of structures. Therefore, this paper analyzes the stability of a natural slope located in Luziânia, Goiás - Brazil and a study of the Probability of Failure by the probabilistic methods FOSM and PEM. In this study was showed distinct safety factors for the analysis in question.**

***Index Terms*—slope stability, probability of failure, FOSM, PEM**

I. Introduction

A very common phenomenon in nature is due to erosion caused by natural factors such as interleaving long periods of drought and rain, or due to anthropogenic processes such as deforestation. Thus, certain natural slopes become a problem due to erosion requiring studies on its stability.

In general, erosion is understood as the soil particles detachment, transport and deposition process caused by erosive agents. It occurs when the transport potential of the erosive agent is higher than the limit of aggregation of soil particles, separating them from each other and allowing their transport [1]

According to [2] the concentration of rainwater flow caused by surface runoff changes results from the disordered process of urbanization, since, with the decrease of infiltration, runoff is increased, drastically changing its local regime: the streets function as water mains, waters captured by the roofs. Intense rainfall causes increased flow, variation in the water table and accelerates erosion processes, leading to an unpredictable increase in size, endangering the residents personal and property safety.

In slope stability analyzes certain methods are most commonly used [3]-[6] and others. However, the deterministic approaches used in conjunction with these models may be error-prone due to disregard of study site lithology variability, because we will never know the precise distribution of any natural phenomenon [7]. Therefore, an advanced method is required to assess the safety of structures, considering variability and uncertainty appropriately [8].

References [9], [10] were concerned with studying slope stability in order to avoid disasters such as landslides. Through scientific studies and technological advancement, stability analysis and slope containment techniques have improved over time. One of the reasons why the region of Luziânia – Goiás/ Brazil, with its tropical climate, is a favorable place for landslide disasters is the high rainfall.

Before beginning the study of stability analysis, it is advisable to understand the causes that may cause slopes to slip. These causes are complex because they involve a multitude of factors that associate and intertwine. Their knowledge allows the engineer carefully choose the solutions that are satisfactory and even predict these alternatives performance. Thus, it is interesting to use the most accurate computational tools available.

For computational analysis, it is necessary to define its geometry and the shear strength parameters of the soil involved such as: specific weight, cohesion, friction angle.

The probabilistic approach becomes a powerful tool for considering soil properties no longer as constants but random variables. Probabilistic methods include the First Order Second Moment (FOSM) method and the Point Estimates (PEM) method.

The FOSM method is based on the first-order truncation of the Taylor series expansion. In addition this method provides analytical approximations for the mean and standard deviation of a parameter of interest [7]. The PEM method is an alternative probabilistic method to the FOSM method developed by [11].

Thus, the application of probabilistic methods associated with slope stability analysis results in important failure probability information. Thus, it has the important advantage of providing a framework for establishing appropriate safety factors and better directs an understanding of the relative importance of uncertainties [12]. Therefore, being for these advantages its application in several studies on probability of failure in slope stability [8], [13], [14]. This research provides pertinent information for the calculation of safety factors in a case of natural slope caused by erosion in the city of Luziânia – Goiás/ Brazil.

II. Main Purposes of Research

The objective of this study is to perform a stability analysis via SLOPE/W of a natural slope caused by

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erosion in the city of Luziânia - GO/Brazil with different methods. In addition, a parametric analysis was performed to verify the importance of cohesion in different layers. Also, apply the FOSM and PEM probabilistic methods to analyze the slope stability and obtain the probability of Failure (P_f).

III. Background of Analysis

In order to improve the understanding of the subjects in the research, the following is a review of the geotechnical literature with emphasis on slope stability. Issues related to the proposed theme were addressed, as well as analysis data such as: location, slope geometry, adopted parameters, related problems, ways of occurrence and causes of slope due to erosion rupture types, stability analysis methods, and computational tools.

A. The Area of Research

Luziânia is a Brazilian city in the state of Goiás. It is the sixth most populous municipality in the state, with an estimated population of 196,864 inhabitants. Its distance from Brasilia - Brazil is about 54km. The overall location of the study area is at 16° 09' 41.9" S; 47° 58' 36.0" W.

B. Soil Parameters

Soil parameters were obtained from 3 Standard Penetration Test (SPT) surveys carried out at the study site. From the tests it was seen that the soil profile is totally clay with varying consistencies (soft, medium, hard and others). The site specific natural weight was obtained by correlating [15] work for clays with varying consistencies (Table I).

$$N_{60} = \frac{N_{SPT} \times E_a}{0,6} \quad (1)$$

Clay cohesion data was obtained primarily by normalizing the N_{SPT} based on the American N_{60} standard [16]:

$$c_u = 5 \times N_{60} \quad (2)$$

Finally, the friction angle was considered as 0 for its highly cohesive characteristic and this did not affect the safety factor calculations of the analyzed slope.

TABLE I. Specific Weight of Clays Soils (Godoy, 1972) [15]

N_{SPT}	Consistence	Specific Weight (kN/m³)
≤ 2	Very Soft	13
3 - 5	Soft	15
6 - 10	Medium	17
11 - 19	Hard	19
≥ 20	Very Hard	21

C. Slope Geometry

The slope analyzed is 3.15 meters high and 5.26 meters long. Thus, it has an angle of approximately 37 degrees. Fig. 1 represents the slope geometry, which has been divided into 10 layers according to lithology.

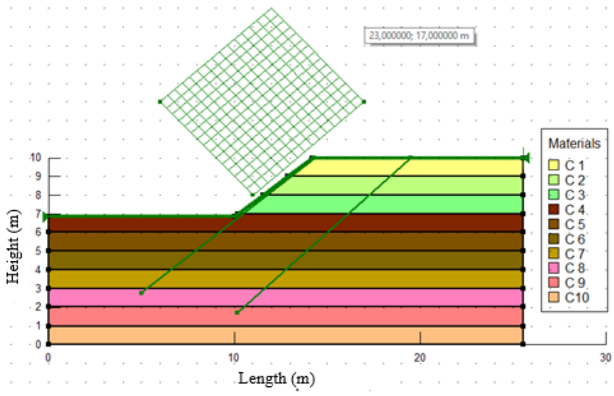

Figure 1. Slope geometry proposed.

D. Slope Stability – Deterministic Methods

The slope stability analysis was performed by GeoStudio 2012 software through SLOPE/W. The deterministic methods used in the analysis were the methods of Morgenster-Price, Janbu, Lowe-Kariafh and Bishop. The option of the slip surface was by grid and radius. These methods were chosen because they are provided by the program and are consecrated in the geotechnical environment.

The soil profile was analyzed using layers at each meter depth with different soil parameters. The lithology analysis was up to 10 meters deep as it was a quota that no longer affected the stability analysis.

E. Probabilistic Methods

In both the FOSM method and the PEM method it was considered that the variability of natural specific weight was zero by depth. Thus, they were considered constant in the failure probability analysis.

For the FOSM method $n+1$ calculations are necessary, because, having n variables, it is also necessary to calculate the F.S. with the average soil parameters. Therefore, considering the first 4 soil layers and only cohesion as a random variable, there were 5 (4 + 1) F.S. calculations by the FOSM method.

For the PEM method it required 2^n calculations. Thus, also considering the first 4 layers, 16 (2^4) F.S.

Cohesion up to the depth of 5 meters was the region most relevant for the stability calculation. Therefore, it considered constant the depth cohesion from 5 meters to 10 meters.

In addition, the reliability index of the safety factor of the structure was calculated by both methods. The method of calculating the reliability index (β) is:

$$\beta = \frac{E[FS] - FS_{critico}}{\sigma[FS]} \quad (3)$$

where:

E [FS] = Safety Factor mean of the probabilistic method;

σ [FS] = Standard deviation of the safety factor obtained by the probabilistic method.

F. Analysis Methods

Most stability analyzes were developed using the limit equilibrium approach. Boundary equilibrium is a tool used by plasticity theory for analysis of body equilibrium, which is hypothesized:

a) Existence of a slip line of known shape: flat, circular, spiral-log or mixed, which delimits, above it, the unstable portion of the slope. This unstable soil mass, under the action of gravity, moves like a rigid body;
b) With respect to a resistance criterion, Morh Coulomb's is normally used along the slip line.

IV. Methodology, Results and Discussions

A. Soil Parameters

Through SPTs and by [15] were found the specific weights of each soil layer (Table II). In addition, it was seen whether the variability through the statistical parameters (standard deviation and variance) was of importance for the analysis of probabilistic methods.

TABLE II. Specific Weight of the Soil up to the Depth of 10m

Layer	γ_{nat} (kN/m^3)	σ	V[x_i]
C1	15,7	1,2	1,3
C2	15,0	0,0	0,0
C3	15,0	0,0	0,0
C4	15,0	0,0	0,0
C5	14,3	1,2	1,3
C6	15,0	2,0	4,0
C7	17,7	1,2	1,3
C8	18,3	1,2	1,3
C9	15,7	1,2	1,3
C10	17,0	0,0	0,0

TABLE III. Correction of the N_{SPT} up to the Depth of 10m

Layer	N_{60} SPT 1	N_{60} SPT 2	N_{60} SPT 3
C1	4,8	1,6	1,6
C2	3,2	1,6	1,6
C3	3,2	1,6	1,6
C4	3,2	1,6	2,4
C5	3,2	3,2	3,2
C6	4,8	4,0	4,0
C7	8,8	6,4	4,8
C8	12,8	7,2	10,4
C9	4,0	6,4	6,4
C10	8,0	8,0	6,4

Cohesion was also analyzed using Eq. (2) and (3). Thus the corrected N_{SPT} is found in Table III and the cohesion calculations and their variability by standard deviation and variance are shown in Table IV.

TABLE IV. Soil Cohesion up to the Depth of 10m

Layer	cohesion (kPa)	σ	V[x_i]
C1	13,3	9,2	84,7
C2	10,6	4,6	21,2
C3	10,6	4,6	21,2
C4	12,0	4,0	15,9
C5	15,9	0,0	0,0
C6	21,3	2,3	5,3
C7	33,2	10,0	100,6
C8	50,5	14,0	195,8
C9	27,9	6,9	47,6
C10	37,2	4,6	21,2

B. Deterministic Method's and Parametric Analisys

The Factor of Safety results by the deterministic approach are illustrated in the Fig. 2-Fig. 5.

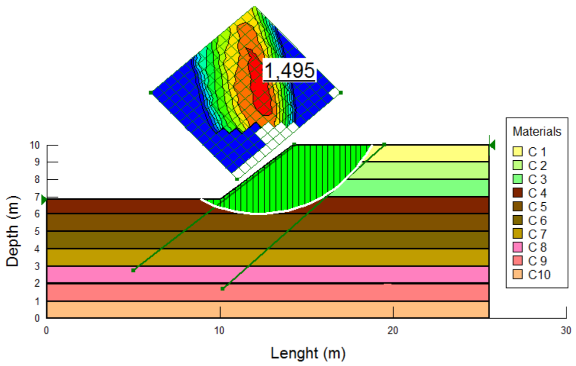

Figure 2. Factor of Safety for Mongenster-Price Method [3].

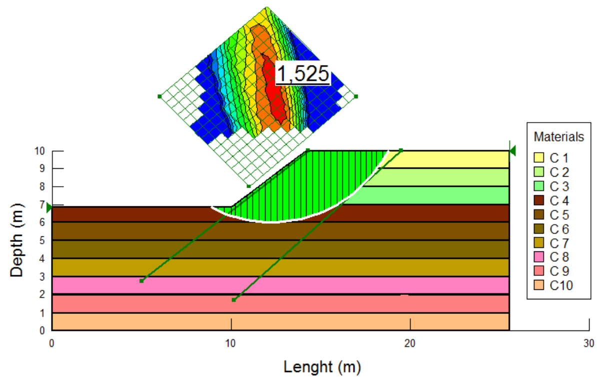

Figure 3. Factor of Safety for Janbu Method [6].

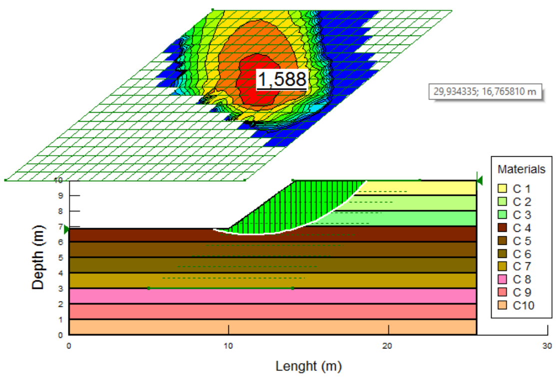

Figure 4. Factor of Safety for Lowe-Karafiath Method [5].

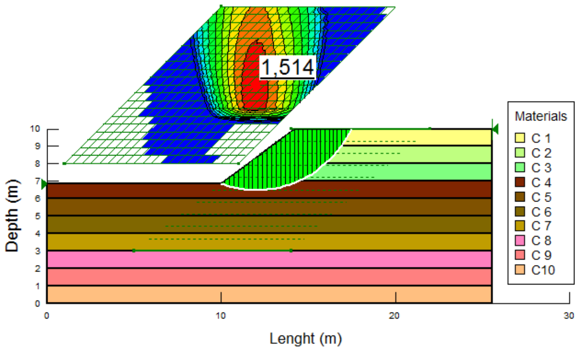

Figure 5. Factor of safety for bishop method [4].

The analysis shows that the Janbu, Bishop and Mongenster-Price's methods obtained relatively close F.S. values. However, the Lowe-Karafiath's method showed to be the highest value amongst them. Moreover, from the analysis the critical slip surface is located for all methods in layer 4. Thus, justifying the reason for using only the first four layers in the probabilistic analysis.

After obtaining the F.S. by the methods mentioned, the cohesion parametric analysis was performed for different methods in the first four layers (Fig. 6-Fig. 9). Thus, it is clear that the Lowe – Karafiath (L-K) method overestimated the F.S. in relation to the others, even with the cohesion variation in the four layers analyzed. In addition, the Mongenster-Price (M-P) and Bishop's methods had identical values in all analyzes.

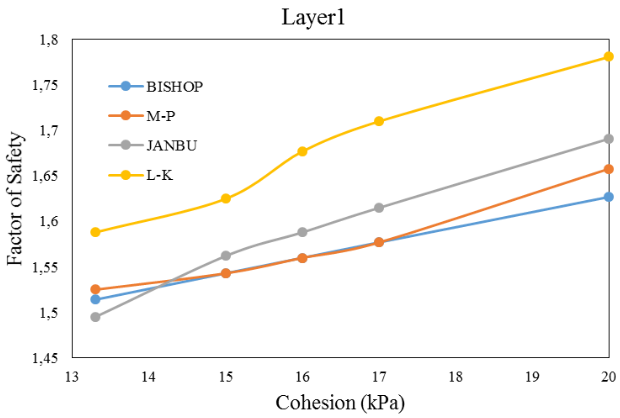

Figure 6. Factor of safety with the cohesion variance for C1.

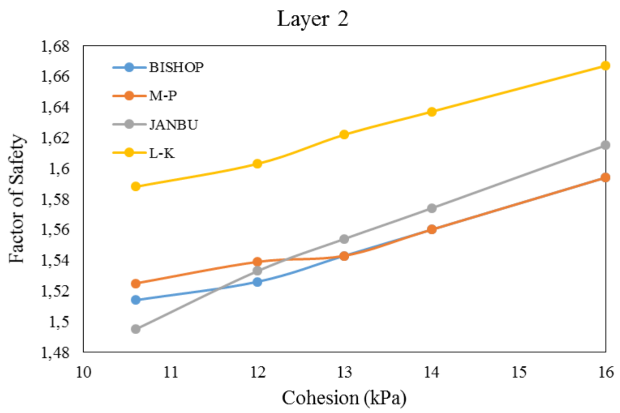

Figure 7. Factor of safety with the cohesion variance for C2.

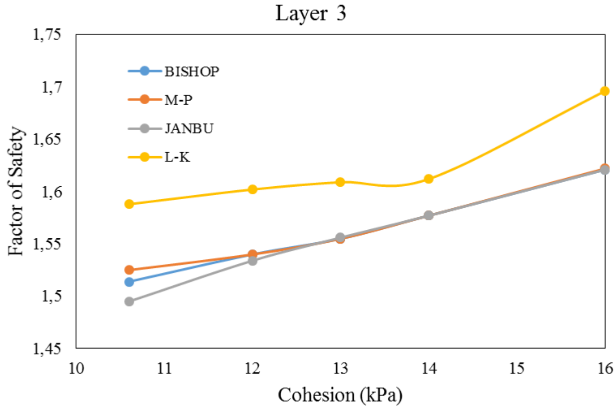

Figure 8. Factor of safety with the cohesion variance for C3.

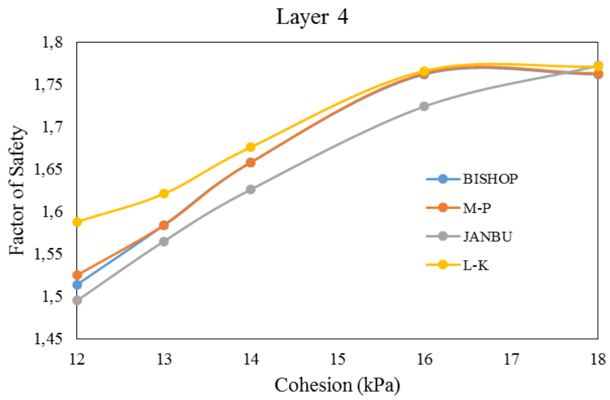

Figure 9. Factor of safety with the cohesion variance for C4.

Finally, the F.S. of layer 4 (Fig. 9) was the one that suffered the largest increase from the parametric analysis performed. This major change is explained by the fact that the layer is the one in which the sliding rupture process occurs. Another important fact is a tendency towards stabilization of the F.S. for layer 4 to cohesion values above 16 kappa, another indicative that this is the layer where rupture occurs and a peak of the F.S. regardless of the cohesion value.

C. FOSM Method

First, the F.S. was calculated using the mean parameters (Morgenstern-Price). The obtained F.S. was 1,525.

From the mean value, all other necessary steps of the FOSM method were calculated. Thus, cohesion increases were made by 10 and 20% for a convergence study. Table V shows the FOSM calculations and the sum of column 6 (0.012) represents the F.S. variance by the FOSM method.

TABLE V. FOSM APPLICATION

x_i	Δx_i	ΔFS_i	$\frac{\partial FS_i}{\partial x_i}$	$V[x_i]$	$\left(\frac{\partial FS_i}{\partial x_i}\right)^2 .V[x_i]$
C1	1,3	0,005	0,004	84,7	1,2 x 10^{-3}
C2	1,1	0,004	0,004	21,2	3 x 10^{-4}
C3	1,1	0,005	0,005	21,2	4,7 x 10^{-4}
C4	1,2	0,030	0,025	15,9	10^{-2}
				V[F.S.]	**0,012**

The F.S. variance allowed the probability of failure (P_f) calculation considering the probability distribution as a normal distribution. Thus, Table VI shows the P_f values for different critical F.S. In addition, the reliability index (β) was calculated by the FOSM method from Eq. (3) and is shown in Table VII.

TABLE VI. PROBABILITY OF FAILURE AND FOSM METHOD

FS_{critic}	**P_f (FOSM) (%)**
1	7,98x 10^{-5}
1,1	5,12x10^{-3}
1,4	12,6
1,5	40,9

TABLE VII. TRUST LEVEL BY THE FOSM METHOD

FS_{critic}	**β**
1	4,8
1,1	3,88
1,4	1,14
1,5	0,23

D. PEM Method

In all, 16 simulations were performed in GeoStudio 2012 to apply the PEM method. Thus, Table VIII shows all simulations with the F.S. obtained. In addition, Table VIII shows the average F.S (*E[F.S.]*) and standard deviation (*σ[F.S.]*) values of the F.S by the PEM method.

TABLE VIII. PEM SIMULATIONS

i	C1	C2	C3	C4	FS
1	14,61	11,69	11,69	13,15	**1,67**
2	14,61	11,69	11,69	10,76	**1,48**
3	14,61	11,69	9,56	13,15	**1,63**
4	14,61	11,69	9,56	10,76	**1,44**
5	14,61	9,56	11,69	13,15	**1,64**
6	14,61	9,56	11,69	10,76	**1,45**
7	14,61	9,56	9,56	13,15	**1,60**
8	14,61	9,56	9,56	10,76	**1,41**
9	11,95	11,69	11,69	13,15	**1,64**
10	11,95	11,69	11,69	10,76	**1,44**
11	11,95	11,69	9,56	13,15	**1,59**
12	11,95	11,69	9,56	10,76	**1,40**
13	11,95	9,56	11,69	13,15	**1,61**
14	11,95	9,56	11,69	10,76	**1,41**
15	11,95	9,56	9,56	13,15	**1,57**
16	11,95	9,56	9,56	10,76	**1,37**
				E[FS]	**1,522**
				σ[F.S.]	**0,106**

As with the FOSM method, the probability of failure (P_f) and the reliability index (β) were calculated for different critical F.S. values. Thus, Table IX has the P_f values and Table X has the calculated β values.

TABLE IX. PROBABILITY OF FAILURE THROUGH PEM METHOD

FS_{critic}	**P_f (PEM) (%)**
1	4,7x 10^{-5}
1,1	3,7x10^{-3}
1,4	12,6
1,5	41,8

TABLE X. TRUST LEVEL OF PEM METHOD

FS_{critic}	**β**
1	4,9
1,1	3,96
1,4	1,14
1,5	0,21

V. STANDARD VALUES OF SAFETY FACTOR

After calculating the safety factors by both methods, a verification was performed with NBR 11682:2009 [17]. Thus, considering the place of residence, recommendations were followed regarding the desired level of safety against loss of life and against environmental and material damage. Therefore, the security level against loss of human life is set high by the intense movement and permanence of people in the building site. In addition, the level of safety against material and environmental damage has a low value for the reduced value of property and environmental accidents. Finally, NBR 11,682 indicates an F.S. of 1,4 for projects with this characteristic.

VI. CONCLUSIONS

Soil variability becomes a very important variable every day in the stability calculations of natural slopes subjected to erosive processes. Thus, the use of probabilistic methods is necessary for greater safety of constructions. Therefore, in this work it was verified the stability of a slope with the following conclusions:

- The deterministic methods (use of the average soil parameters) found a relevant factor of safety (F.S.) for slope stability;
- The parametric analysis showed a more sensibility of layer 4 for variations of cohesion. The reason is because the layer 4 is where is located the sliding surface;
- The mean F.S for the FOSM (1.525) and PEM (1.522) methods were close, showing the possibility of being the actual mean F.S. of the slope;
- Both methods had close standard deviations;
- Both methods had close probability of failure (P_f) and generally, the PEM method had slightly lower values;
- The reliability index (β) of both methods were also close.
- From the analysis is concluded by both methods that the probability of failure is high (12.6%). It can be concluded that intervention works are necessary in order to raise the F.S. of the site and decrease the probability of failure.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Moisés A. C. Lemos was responsible for all F.S. analysis and simulation in the GeoStudio program. Arthur D. Dias was responsible for obtaining the parameters in the literature and for writing the article. André L. B. Cavalcante was responsible for suggesting the development of the work, to correct all the results and checking the written work.

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