Approach to Calculating the Failure Probability of Bearing Capacity of Augercast Pilling Foundations Using the FOSM Method

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Abstract—**The predicting difficulty of bearing capacity of foundations becomes a major problem due to the constructions with rigorous construction processes. Hence, the soil spatial variability is often ignored in the calculations of bearing capacity of deep foundations. Consequently, the use of statistic associated with bearing capacity calculations has added important failure probability information of piles foundations. Thus, this work presents a methodology for calculating the probability of failure of bearing capacity using the probabilistic method First Order Second Moment (FOSM). The data used come from a residential building in the city of Águas Claras / Federal District - Brazil. Finally, this work provided a methodology for calculating the probability of failure taking into account soil lithology and spatial variability.**

Index Terms—**Bearing Capacity, FOSM, empirical methods, Augercast Pilling Foundations**

I. Introduction

Geotechnical Engineering has been undergoing major changes due to the need for performance indicators (safety factors, structure sizing, and bearing capacity) to inform the real safety of buildings. In the course of engineering projects the deterministic approach is used discriminately and in such a way that the works have complete reliability. However, cases in which works had adequate performance indicators and yet obtained ruptures brought the need for approaches that included soil variability, whether spatial or temporal.

The parametric approach in the study of soils also made an important contribution by considering certain soil parameters as variables. However, setting the range of values becomes a challenge due to the knowledge of these values or the performance of a large number of tests. Thus, the probabilistic methods have gained great importance in recent decades by the insertion of soil variability and computational advancement. According to [1], the probabilistic approach requires 10 to 1000 times more computational resources than deterministic analyzes. Therefore, an advanced method is required to assess the safety of structures, considering variability and uncertainty appropriately [2].

The main advantage of probabilistic methods is that they transform independent variables into random variables, thus allowing the analysis of these variables and performance indicators into probability distributions. Among the probabilistic methods is the FOSM, which makes use of second moment statistical parameters (mean and variance). A first order Taylor approximation is used to linearize the performance function in the mean values of random variables [3].

Thus, probabilistic methods have been adding pertinent information to the geotechnical study due to soil dispersion. As for this dispersion is clearly seen in the load-bearing studies of foundation structures and the need for reliability and failure probability insertion [4], [5].

Soil variability is mainly seen in Standard Penetrations Test (SPT) reports which are commonly used in foundation engineering to calculate bearing capacity. Although SPT reports provide relevant information through a simple test methodology, it has been seen in recent years as a problem due to the lack of a correct application methodology.

Therefore, the need for methodologies that make appropriate use of data obtained from SPTs reports is important and necessary. In addition, the introduction of the probability of failure of foundation structures is becoming increasingly necessary in enterprises that require high building reliability. According to [6], it is considered that the likelihood of rupture linked to foundation projects should be between 10^{-4} (1 / 10,000) to 4×10^{-4} (1 / 2,500).

Currently, the importance of probabilistic methods in geotechnical engineering is present in several studies such as slope stability [1], [7], dams [8], foundation bearing capacity and others.

II. Objective

The main objective of this work is to apply a methodology for calculating the probability of failure of pile foundation bearing capacity using the FOSM probabilistic method. The probability of failure was calculated by depth (each meter) and by varying the

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number of piles. In addition, for bearing capacity calculations, the semi-empirical methods of Aoki-Velloso [9] and Décourt-Quaresma [10] with the adaptations of [11] were used. The data used are from the city of Águas Claras / Federal District, where a residential building is currently built.

III. Background of Analysis

A. Empiric Bearing Capacity Methods

According to [12], in Brazil and worldwide, the methodology used in deep and direct foundation projects uses the results of the Standard Penetration Test (SPT).

1) Aoki & Veloso Method (1975) [9]

The method of Aoki-Velloso was developed through correlation between static (cone) and dynamic (SPT) penetration. The bearing capacity is calculated by Equation (1):

$$R = \frac{K.N_p}{F_1} A_p + U \sum (\alpha \frac{K.N_L}{F_2} \Delta_L) \qquad (1)$$

where:

N_p = soil penetration resistance index at the pile tip;

A_p = stake tip area [m²];

K = parameter used to correlate the tip resistance of the CPT test with SPT [kN m²];

U = perimeter of pile cross section [m];

α = lateral resistance and cone tip correction factor in the CPT test;

N_L = average soil penetration resistance index along the pile;

ΔL = height of the considered layer [m];

F_1 = peak resistance correction coefficient [dimensionless];

F_2 = lateral resistance correction coefficient [dimensionless].

2) Decourt & Quaresma Method (1978) [10]

Based on SPT test results, the allowable bearing method proposed by Décourt-Quaresma, which was modified by [11], can be described by Equation (2):

$$R_{Adm} = \frac{N_p.\alpha.K.A_p}{4} + \frac{U.\beta}{1,3}.10\left(\frac{N_m}{3}+1\right).\Delta_L \qquad (2)$$

where:

N_p = soil penetration resistance index at the pile tip, which is represented by the average of the values at the depths of the pile tip, the immediately preceding level and the posterior one;

α and β = values depending on soil type and foundation structural element;

K = coefficient relating tip resistance as a function of soil type [kN m²];

A_p = stake tip area [m²];

U = pile cross section perimeter[m];

N_m = average soil penetration resistance index along the pile;

ΔL = height of the considered layer [m].

B. FOSM Method

The Taylor series expansion for a multivariable function *f(xi)* using only the linear component can be shown by Equations (3) and (4):

$$y = f(x) = f\left(x_1, x_2, ..., x_n\right) \qquad (3)$$

and

$$y = f\left(x\right) = f\left(\overline{x}_i\right) + \sum_{i=1}^{n}\left(x_i - \overline{x}_i\right)\frac{\partial y}{\partial x_i} \qquad (4)$$

where:

y = the function to be obtained;

x_i (for i = 1 to n) = the indepented variables;

n is the number of independent variables;

$\overline{x}_i$ is the average value of variable x_i.

Thus, by manipulating Equations (3) and (4) it is possible to demonstrate that the value of y (*E [y]*) and the variance of y (*V[y]*) can be obtained by Equations (5) and (6), respectively:

$$E\left[y\right] = f\left(\overline{x}_i\right) + \frac{1}{2}\sum \frac{\partial^2 y}{\partial x_i \partial x_j}\operatorname{cov}(x_i, x_j) \qquad (5)$$

and

$$V\left[y\right] = \sum\left[\left(\frac{\partial y}{\partial x_i}\right)^2 V[\mathrm{x}_i]\right] + 2\sum\left[\frac{\partial y}{\partial x_i}\frac{\partial y}{\partial x_j}\operatorname{cov}\left(x_i, x_j\right)\right] \qquad (6)$$

where:

cov (x_i, x_j) = covariance of variables x_i and x_j.

However, equations (5) and (6) are commonly calculated by disregarding the covariance portion. Thus, both equations above require the calculation of the derivative of function (y) in relation to the variables, calculated according to Equation (7):

$$\frac{\partial y}{\partial x_i} \approx \frac{f\left(\overline{x}_1, ..., \overline{x}_i + \Delta x_i, \overline{x}_n\right) - f\left(\overline{x}_1, ..., \overline{x}_i - \Delta x_i, \overline{x}_n\right)}{2\Delta x_i} \qquad (7)$$

$\Delta x_i = a_p\ \sigma_i$, a_p being a proportionality coefficient determined by convergence test and σ_i is the standard deviation of the variable x_i.

C. Confidence Level for the Mean

Confidence level for the mean is a methodology that aims to determine a confidence interval based on the sample or population standard deviation and sample size. Thus, it is suggested that in cases of not knowing the population standard deviation and the sample is smaller or equal 30 one should use the estimation through the t or Student distribution. In addition, Equation (8) can calculate the confidence range for Student distribution:

$$\left[\overline{X} - t_{\alpha/2}\left(s/\sqrt{n}\right); \overline{X} + t_{\alpha/2}\left(s/\sqrt{n}\right)\right] \qquad (8)$$

where:

$\overline{X}$ = the mean value of the variable;

$t_{\alpha/2}$ = is the value in the Student distribution for a significance level α;

s = sample standard deviation;

n = sample size.

IV. METHODOLOGY

The methodology used (Fig. 1) is based on obtaining the variability of SPT reports. Thus, the N_{SPT} was analyzed by meter (depth) and its statistical parameters (mean, standard deviation and variance) calculated. After that, the deterministic bearing capacity was calculated, that is, from the average parameters was calculated the bearing capacity for both semi-empirical methods.

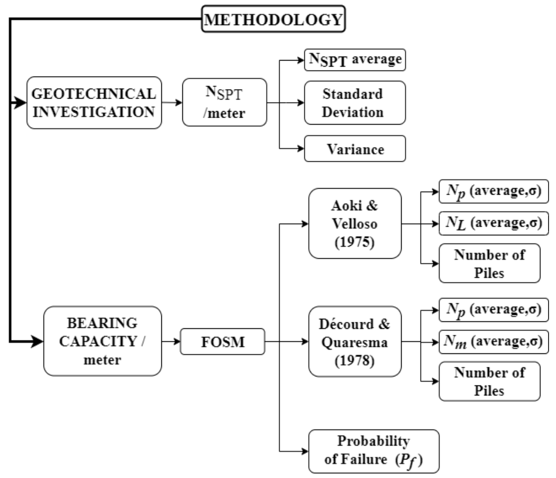


Figure 1. Methodology of the application of the FOSM method on foundation bearing capacity.

After the deterministic bearing capacity is calculated, the FOSM method was applied. For this it was necessary to obtain the variance of the bearing capacity using Eq. [6] disregarding the covariance portion. In addition, the derivative of the equations of the semi-empirical methods were performed in relation to the variables that in this case was the N_{SPT} per analyzed layer. Thus, obtained the bearing capacity variance per layer, the probability of failure (P_f) calculation was performed considering a normal probability distribution. In addition, the average bearing capacity was the number of piles (n_e) times the average bearing capacity (deterministic).

The probability of failure calculation using the normal distribution can be done using computational tools such as Excel. In Excel just need to use the function described by Equation (9):

$$P_f = \text{NORM.DIST}\left(F_n; n_e.R_{med}; \sigma; \text{TRUE}\right) \quad (9)$$

where:

F_n = load from structural calculation [kN];

n_e = number of piles;

R_{med} = bearing capacity calculated with mean N_{SPT} of each layer [kN];

σ = standard deviation calculated by the FOSM method [kN];

TRUE = Excel will return the cumulative distribution function.

V. MATERIALS

The study site is in the administrative region of Águas Claras / Federal District – Brazil, which is approximately 20 km from Brasília / Federal District - Brazil.

In all, 8 simple percussion probes were performed until it was found to be impenetrable. Of these, 2 were rotated to a depth of 19 meters.

It is important to note that the excavation of the piles were performed by continuous propeller and the diameter of the piles were 40 cm and 50 cm. However, the 50 cm diameters were only used for large radiers that were designed, so the 40 cm diameters were used for the calculations. In addition, this work obtained the loads of the residential building from the structural calculation. In this work was used the highest load value for the probability of rupture (P_f). The highest loading value for this building was 6336 kN.

VI. RESULTS

First, from the N_{SPT} reports it was possible to obtain the statistical parameters (mean, standard deviation and variance). Both data are shown in Table I and Table II. Thus, it is possible to observe that the largest dispersions occurred in the first layer, the sixth layer and the ninth layer.

TABLE I. N_{SPT} FROM THE DEPTH SURVEY REPORT (Z)

z (m)	SP1	SP2	SP3	SP4	SP5	SP6	SM01	SM02
1	35	30	11	2	7	6	23	10
2	6	7	5	3	11	7	25	10
3	6	7	6	5	24	13	4	9
4	12	14	11	9	27	12	7	6
5	12	16	21	13	33	16	6	10
6	25	26	42	9	40	19	11	18
7	31	37	45	21	46	34	34	24
8	40	44	53	33	50	37	37	24
9	42	46	57	39	52	50	50	23
10	45	47	61	50	53	59	50	38

TABLE II. N_{SPT} FROM THE DEPTH SURVEY REPORT (Z) STATISTICAL PARAMETERS

z (m)	N_{SPT} average	Standard Deviation	Variance
1	15,5	12,2	148,9
2	9,3	6,9	47,1
3	9,3	6,6	43,4
4	12,3	6,5	42,8
5	15,9	8,2	67,8
6	23,8	12,2	148,5
7	34,0	8,9	78,9
8	39,8	9,3	86,8
9	44,9	10,5	110,4
10	50,4	7,4	55,4

After obtaining these values, the bearing capacity was then calculated by means of the average N_{SPT}, since this value is of great importance for the following calculations of the FOSM method. Therefore, Fig. 2 shows the average bearing capacity values for Aoki-Velloso and Décourt-Quaresma. Note that the bearing capacity values proposed by Aoki-Velloso are higher than those proposed by Décourt-Quaresma.

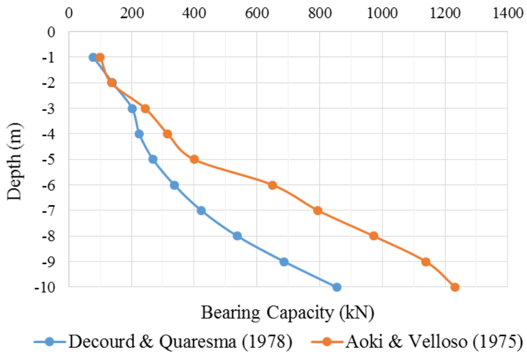


Figure 2. Bearing capacity using mean NSPT values.

The parameters K, α, F_1, F_2 and pile diameter mentioned in Eq. (1) were considered constant. This choice is due to the fact that K and α have low dispersion in the analyzed soil layers and, thus, were considered constant by depth. K, α are values suggested by Aoki-Velloso, F_1 and F_2 were values suggested by [13] for continuous Augercast excavations. A safety factor of 2 was considered for the allowable bearing capacity (R_{Adm}) of the Aoki-Velloso method.

Regarding the method of Décourt-Quaresma, the parameters α, β, K mentioned in Eq. (2) were also considered constant. The parameters α, β and K were used as suggested by [11].

TABLE III. FOSM Method Calculations for 10 m Quota for Decourt & Quaresma Method

x_i		$\partial R / \partial x_i$	V[x_i]	$(\partial R / \partial x_i)^2$ x V[x_i]
N_1	15,5	3,22	148,9	1545,5
N_2	9,3	3,22	47,1	488,7
N_3	9,3	3,22	43,4	450,1
N_4	12,3	3,22	42,8	444,2
N_5	15,9	3,22	67,8	704,3
N_6	23,8	3,22	148,5	1541,8
N_7	34,0	3,22	78,9	818,7
N_8	39,8	3,22	86,8	901,0
N_9	44,9	0,77	110,4	64,7
N_{10}	50,4	0,79	55,4	34,2
N_{11}	50,4	0,79	55,4	34,2
			V[R]	**7027,5**

TABLE IV. FOSM Method for Aoki & Veloso

x_i		$\partial R / \partial x_i$	V[x_i]	$(\partial R / \partial x_i)^2$ x V[x_i]
N_1	15,5	1,53	148,9	349,3
N_2	9,3	1,79	47,1	151,3
N_3	9,3	2,36	43,4	241,5
N_4	12,3	2,08	42,8	184,6
N_5	15,9	1,72	67,8	201,1
N_6	23,8	1,81	148,5	486,5
N_7	34,0	1,81	78,9	258,4
N_8	39,8	1,85	86,8	298,3
N_9	44,9	1,85	110,4	379,5
N_{10}	50,4	1,85	55,4	190,5
N_{11}	50,4	15,14	55,4	12693,2
			V[R]	**15434,2**

Table III shows the calculation values of the FOSM method for the 10-meter dimension of the Aoki-Velloso and Décourt-Quaresma methods, respectively. In addition, the sum of column 5 of Table III and Table IV refers to the bearing capacity variance value of each method. It is also important to note that in the same way as in the 10 meter elevation, the same calculations were performed for the lower quotas, varying the number of piles.

TABLE V. Probability of Failure (P_f) for Different Number of Piles at 10 m Elevation Aoki & Veloso

Piles	F_n (kN)	Standard Deviation	$R_{,méd}$ (kN)	P_f (%)
4	6336	124,2	4928,8	100,0
5	6336	124,2	6161,0	92,1
6	6336	124,2	7393,2	$8{,}7\times10^{-16}$

TABLE VI. Probability of Failure (PF) for Different Number of Piles at 10 m Elevation Decourt & Quaresma

Piles	F_n (kN)	Standard Deviation	$R_{,méd}$ (kN)	P_f (%)
7	6336	83,8	5977,8	100,0
8	6336	83,8	6831,8	$1{,}7\times10^{-7}$
9	6336	83,8	7685,8	$1{,}2\times10^{-56}$

From the variance calculations by the fosm method and considering that the bearing capacity has a normal distribution curve, the probability of failure according to Eq. aoki-velloso was calculated. Table V and Table VI shows the P_f for both methods at a depth of 10 m. It is observed that the bearing capacity value was higher for aoki-velloso causing smaller numbers of piles. However, the decrease in the probability of failure in the Décourt-Quaresma method decreases much more sharply due to the smaller variability (variance) of the load capacity calculated by the method.

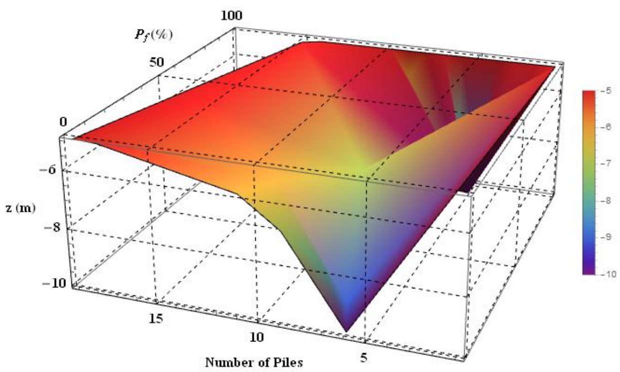


Figure 3. Probability of failure (P_f) x laying height (z) x number of piles. Aoki and Velloso's method (1975). (b) method of Décourt and Quaresma (1978).

Due to the possibility of choosing the foundation depth, the number of piles that have a certain probability of failure to suit the work in question, the same calculations were performed at various depths. Therefore, Fig. 3 shows the results of the most realistic depth calculations for pile number for the two semi-empirical bearing capacity methods. In Fig. 4 is shown that the 3D graphics have the depth legend in the left of them. Moreover, in Fig. 4 it is possible to see that in the P_f plane close to zero the number of piles decreases exponentially with the foundation elevation. Therefore, smaller P_f are expected for larger depths with smaller number of piles, which is in line with reality.

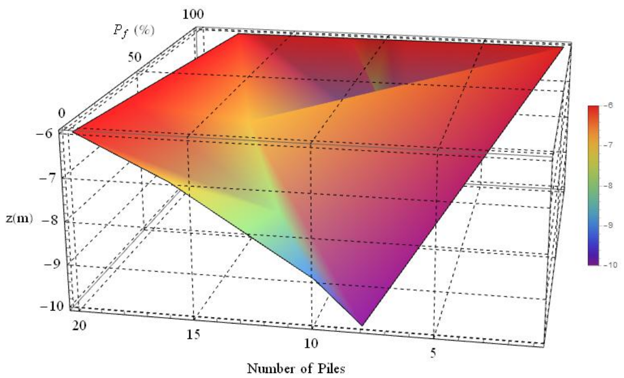


Figure 4. Probability of failure (P_f) x laying height (z) x number of piles. Method of Décourt and Quaresma (1978).

The main interest in the graph in the Fig. 3 and Fig. 4 lie in the failure probability zone between 0 and 1. Thus, Fig. 5 and Fig. 6 provide a better view for the correct choice of the number of piles per depth for both empirical methods. The vertical dashed line represents the recommendation of [6] and the values to its left are where theoretically tolerable P_f values for foundation works would be. Therefore, as expected, the Aoki-Velloso method predicted lower number of piles for smaller P_f than recommended.

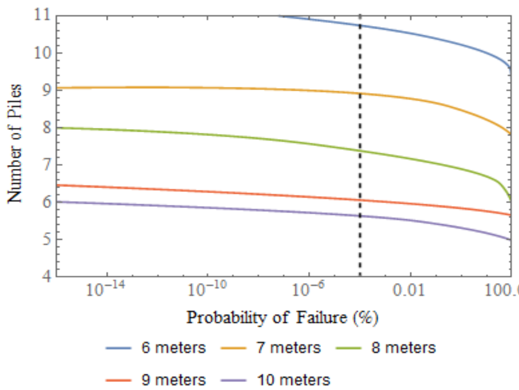


Figure 5. Probability of failure (P_f) x number of piles at different depths. Method of Aoki Velloso.

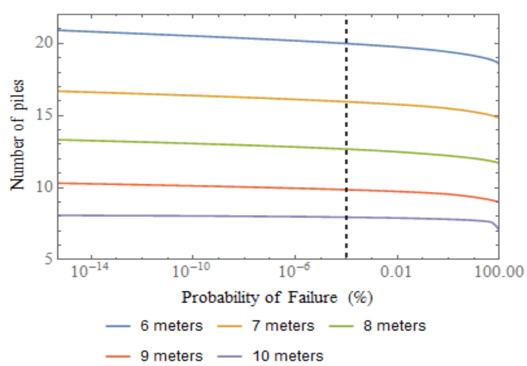


Figure 6. Probability of failure (P_f) x number of piles at different depths. Method of Décourt and Quaresma.

One of the advantages of the FOSM method is the indication of the contribution of the variables to the calculation of the performance indicator, here being bearing capacity. Therefore, this contribution was verified at the 10 meter quota for both semi-empirical methods. In Fig. 7 and Fig. 8 we have such an analysis and it is concluded that for the Aoki-Velloso method the contribution is in a major way from the stake tip N_{SPT}.

The Décourd-Quaresma method contributes significantly from the N_{SPT} along the pile shaft. In addition, when calculating the bearing capacity variance, the Décourd-Quaresma method has a higher sensitivity to the N_{SPT} variance values when they represent the pile shaft. Thus, in Fig. 9, N_1 and N_6 have greater contribution because they have greater dispersion and because they represent the stake shaft at the 10-meter height.

From the calculations of the bearing capacity variance by the FOSM method, it was possible to obtain the standard deviation by changing the foundation seating depth. Thus, Fig. 9 shows the standard deviation of bearing capacity by both methods. The Aoki-Velloso method has shown higher bearing capacity values and, consequently, lower P_f values, however it has higher standard deviation values. This means that P_f decreases more smoothly by varying the number of piles for the same pile settlement account. For the Décourd-Quaresma method there was a tendency to normalize standard deviation with depth. In general, both methods had a greater dispersion in bearing capacity values with increasing depth.

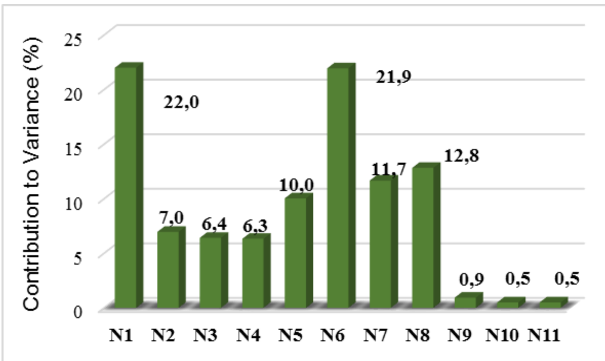


Figure 7. Contribution of the N_{SPT} for the calculation of the bearing capacity variance at z = 10m. Aoki & Velloso Method.

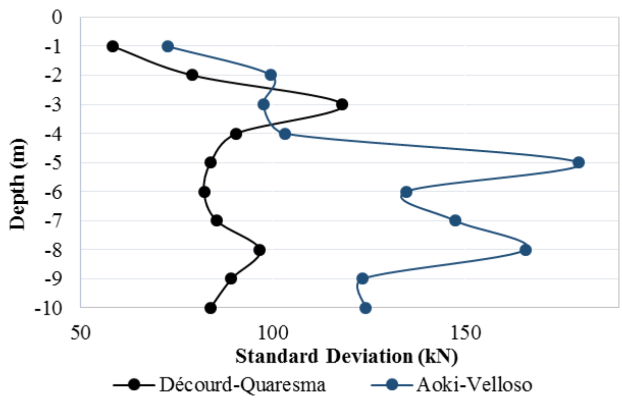


Figure 8. Contribution of the N_{SPT} for the calculation of the beating capacity variance at z = 10m. Decourt & Quaresma Method.

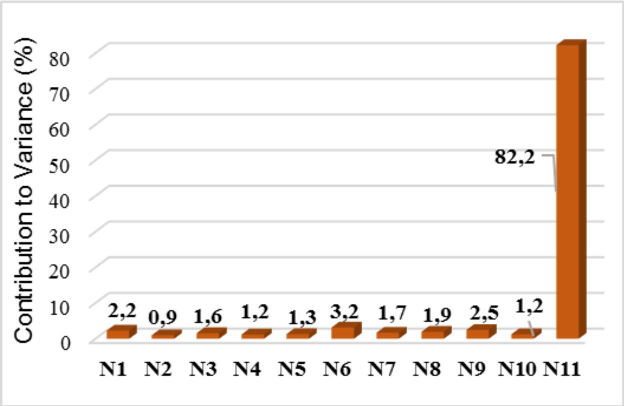
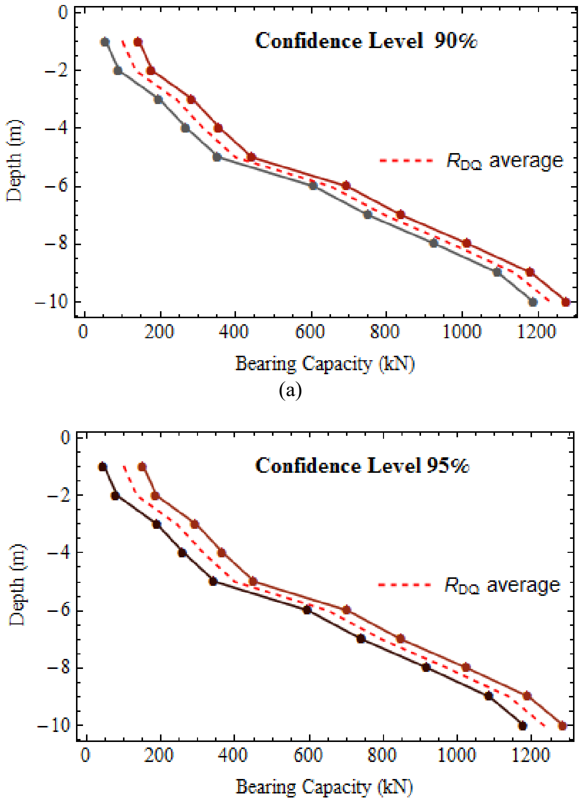


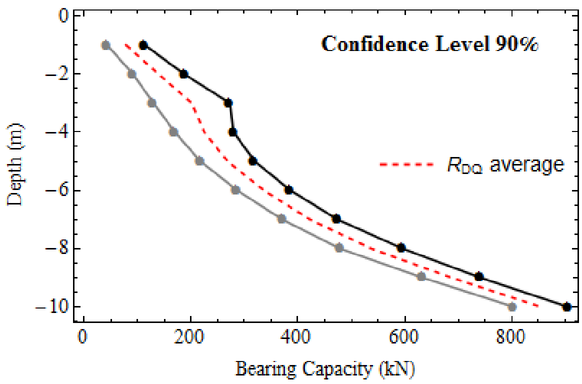
Figure 9. Standard deviation of bearing capacity relative to pile setting account for semi-empirical methods.



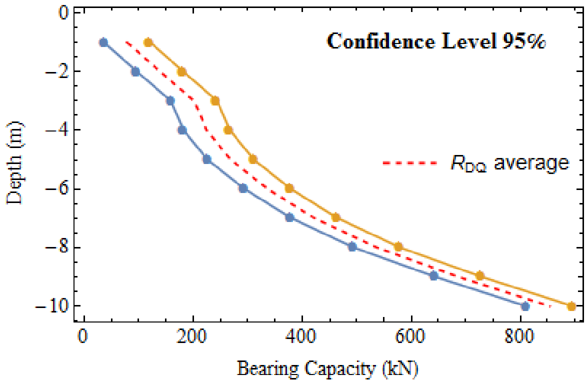
(a)

(b)

Figure 10. Bearing capacity reliability of the Aoki-Velloso method. a) confidence level of 90%; b) confidence level of 95%.



(a)



(b)

Figure 11. Bearing capacity reliability of the Décourd-Quaresma method. a) confidence level of 90%; b) confidence level of 95%.

Finally, a confidence range to mean estimation was made using the t or Student distribution to obtain the appropriate bearing capacity range for both methods. The Student distribution was chosen because the sample consisted of only 8 SPT, being less than 30. Thus, Fig. 10 (a, b) and Fig. 11(a, b) show the values with 90 and 95% confidence levels for the Aoki-Velloso and Décourd-Quaresma methods, respectively. The $t_{\alpha/2}$ values used from the t distribution are 2.06 and 1.71 for a confidence level of 95 and 90%, respectively. Thus, applying Eq. (8) the confidence intervals of both methods were obtained.

VII. Conclusions

Foundation structures are the part of construction that may have greater design and construction doubt due to the large variability of soil in the area to be built. Thus, load-bearing studies that take into account this dispersion and still provide information on the probability of failure are of great value. Therefore, from the proposal of this work of bearing capacity calculation through semi-empirical methods commonly used in foundation engineering, it can be concluded that:

- The soil of the region of Águas Claras / Federal District - Brazil presents a great variability in the initial layer, despite a higher resistance compared to the underlying layers;
- The Aoki-Velloso (A-V) method showed higher bearing capacity values compared to Decourd-Quaresma (D-Q) for the region's soil;
- The bearing capacity variance by the A-V method has a value slightly more than 2 times that of D-Q;
- The variance values are related to the constants adopted by the models and the bearing capacity calculation method;
- The probability of failure (P_f) of A-V was lower than D-Q, but the decrease of P_f by D-Q was more pronounced as the number of piles increased. Fact is related to the largest dispersion (standard deviation) found by A-V;
- The contribution of the N_{SPT} to the bearing capacity variance of the A-V method is expressively derived from the pile tip;
- The contribution of the N_{SPT} to the bearing capacity variance of the D-Q method has greater sensitivity to the

N_{SPT} variance values along the pile shaft. The pile tip N_{SPT} have irrelevant participation;

• The standard deviation values of bearing capacity by A-V were practically higher than those of D-Q. In addition, both methods had greater dispersion for greater depths;

• Due to the greater dispersion of A-V, therefore, there was a greater confidence interval compared to D-Q.

Finally, this work presents a methodology for calculating the probability of failure of foundation bearing capacity through semi-empirical methods and using the probabilistic FOSM model. The limitations of the model are due to the need to adopt a (normal) probability distribution of bearing capacity. Accurate models, such as Monte Carlo, may prove to be of great importance in the proposed methodology. However, the greater ease of application of FOSM and of providing the contribution of variables in the variance of bearing capacity justifies the adoption of the model.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Arthur D. Dias was responsible for obtaining Standard Penetration Tests and for writing the article. Moisés A. C. Lemos was responsible for developed the probability of failure approach of piles bearing capacity and obtain the results. André L. B. Cavalcante was responsible for suggesting the development of the work, to correct all the results and checking the written work. Renato P. Cunha suggested the area of research and revised the method applied and results.

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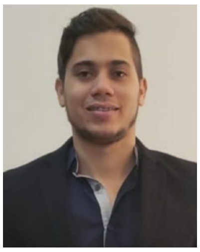

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