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Reliability and Safety Geotechnical of a Combined Pile Raft Foundation

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Abstract

Reliability and safety concept has increasing importance within engineering and are being widely used in civil construction works enabling a higher level of safety and project design risk control. This paper presented reliability and safety criteria analysis, as well as the probability of failure of a reinforced concrete wall building executed with combined pile raft foundation (CPRF) located in the Metropolitan Region of Recife (MRR), Pernambuco, Brazil. It was adopted Cintra and Aoki (2010) and Aoki (2011) methodology for reliability analysis. The pile bearing capacity was estimated through the semi-empirical methods suggested by Aoki-Velloso (1975), Décourt-Quaresma (1978) and Teixeira (1996). A statistical analysis was performed, and probability density functions of resistance and solicitation curves were constructed. Although, Décourt-Quaresma method has the lowest variation in the estimated values of pile load capacity in both models and it was obtained the lowest reliability index and the highest failure probability among the three methods used. The Aoki-Velloso method, even having the largest dispersion in the results, has the highest reliability index and the lowest probability of failure, being the only method to fit the requirements of Meyerhof (1995) and the European Code.

Keywords: Reliability and security. Probability of failure. Bearing capacity.

INTRODUCTION

The Brazilian tradition of geotechnical design of piles foundations consists in the determination of the allowable load using the concept of global safety factor. NBR 6122:2019, a Brazilian standard of foundations design and execution, also prescribes the method and project values, based on partial safety factors, widely used by designers of structures. Aoki and Cintra (2010) affirms that the method, which aims to verify the ultimate limit state, is insufficient for comprehensive analysis of the safety of a foundation, thus becoming an outdated concept to consider that safety factors prescribed in standards guarantee the absence of ruin risk. It is also necessary to verify the probability of foundation ruin through of the reliability analysis.

Some studies highlight the importance of reliability analyses applied to Geotechnical Engineering, which can be mentioned: Duncan (2000), Aoki (2002), Phoon et al (2003), Silva (2003), Silva (2006), Teixeira (2012), Li et al. (2015), Souza and Albuquerque (2016), Neves and Reis (2017), Beloni et al. (2017), Naghibi and Fenton (2017), Tang and Phoon (2018), Silva Neto and Oliveira (2018), Haldar (2019), Romanini (2019), Romanini et al. (2019), Velloso (2019) and Tang and Phoon (2019).

New construction systems use becomes increasingly important in the construction market, searching the best performance and cost-benefit of the enterprises. The combined pile raft foundation (CPRF) has great capacity for acceptance in structures on soft soil, due to its excellent performance in the control of settlements and bearing capacity of two types of foundation combined in a single system, can be economically designed for constructions. In the CPRF system, loads are absorbed by the two structures (raft and piles) thus favoring safety for the model. Rincon (2016) states that in the CPRF system one structure compensates for the failures of the other, the raft being responsible for standardizing and absorbing loads and the piles acting by good performance in the total settlements.

For effective elaboration of a foundation project, it is known which parameter can influence the most in the variability of load capacity values, thus providing a higher probability of ruin and a lower reliability, generating more risk for the enterprise.

This paper presents reliability and safety criteria analysis, as well as the probability of failure of a reinforced concrete wall building executed with combined pile raft foundation (CPRF) located in the Metropolitan Region of Recife (MRR), Pernambuco, Brazil, from comparative analyses of bearing capacity estimates and analysis of probability density and probability of failure curves.

This study is included in the research project entitled "Study of CRPF of buildings with and concrete wall construction system", in which was already carried out in the same area: Analysis of the foundations project using finite element methods in the analysis of load test (Silva, 2021); Evaluation of SSI with monitoring of settlements and analysis of the influence of the constructive sequence on the performance of CRPF (Silva Junior, 2021); Evaluation of the settlements by angular distortion (Jordão Júnior, 2021; Jordão Júnior et al., 2022); and analysis of different scenarios of support of a foundation by pile raft (Alves, 2021; Alves et al. 2022); and, Reliability and safety of a foundation with CRPF (Silva, 2021).

METHODOLOGY

General Characteristics of the Site

The study was performed in project of the residential condominium, located in the city of Jaboatão dos Guararapes belong to the MRR, Pernambuco, Brazil. The development consists of 14 (fourteen) blocks of 05 (five) floors (ground floor + 04 floors), with linear distribution of loads for the foundation, carried out through reinforced concrete walls molded on site. The analyses were performed for block 13, can be considered for the other blocks.

In general, a profile of the soil with heterogeneous foundation, composed initially of a layer of sand with organic matter, soft to little compact, varying up to 6.0 and -7.0 m of depth, followed by a layer of sand, medium compact, ranging up to +1.0 to -11.0 m of depth. The next layer is composed of a silt-clayey sand, little compact, ranging up to -11.0 to -21.0 m of depth, ending with a layer of sand, medium compact to compact, up to the limit of the polls, in -18.0 to -25.0 m of depth. The groundwater level was found around the +7.0m of depth.

Due to the geotechnical characteristics of the soils and the linear transmission of loads from the building to the ground, it was decided to perform a CPRF.

For each apartment block, a single raft with a thickness of 25 cm and an approximate area of 528 m^2 was executed, made of structural concrete molded in the site, with compression resistance of 40 MPa. Figure 1 shows the location and frame of the raft, with the demarcation of the crown blocks of the piles. The raft is generated and delimited with a slat of structural masonry, and on it is born a system of wood shape that delimits the concreting of the foundation (Figure 2).

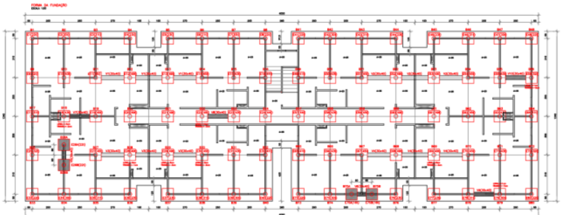
Figure 1. Located of raft and frame

Figure 2. Construction of raft

Source: The authors.

In total, 1490 prefabricated concrete piles were set, square cross section, hollow and with a side of 25 cm, with a thickness of 12 cm and CA-50 steel frame. The piles have variable lengths between 12 and 25 m. Figure 3 shows the arrangement of the CPRF.

Figure 3. Arrangement of the piles in the raft



Source: The authors.

METHODOLOGY USED IN THE RELIABILITY ANALYSIS OF PILES

To perform the analysis of the reliability and safety criteria of the CPRF initially it is necessary to estimate the load capacity values for the piles. For the determination of these values, the semiempirical methods of Aoki-Velloso (1975), Décourt-Quaresma (1978) and Teixeira (1996) were used. Based on these results, the variation of the statistical results of resistance for the methods used and the statistical results of the request was calculated in order to find the values of soil resistance's variation coefficient (v_r) and the of solicitation's variation coefficient (v_S). From the results obtained, the analysis of probability density curves and the verification of the calculated results for the probability of ruin and reliability were performed. The methodology adopted for reliability analysis was suggested by Cintra and Aoki (2010) and Aoki (2011).

Two load distribution models were considered among the four models established in Alves (2021): (a) Model 1, in which the piles were modeled with rigid supports and the raft remains free; (b) and Model 2, in which the piles were modeled with rigid supports and the soil in contact with the raft with linear elastic supports (linear spring).

The methodology for the analysis and reliability criteria was suggested by the authors Cintra (2010) and Aoki (2011). Both believe that the population to be analyzed is finite and that the probability density curves, both resistance (R) and solicitation (S) curves obey a normal symmetrical distribution (Aoki, 2002).

The variability of Resistance (R) and Solicitation (S) can be expressed by the resistance coefficient of variation (Equation 1) and solicitation coefficient of variation (Equation 2)

$$v_r = \frac{\sigma_r}{R_{méd}} \qquad \text{Eq. 1}$$

$$v_s = \frac{\sigma_s}{S_{méd}} \qquad \text{Eq. 2}$$

Where: σ_r - resistance standard deviation; R_{med} - average resistance value; σ_s – solicitation standard deviation; S_{med} - average value of the solicitation.

The global safety factor (SF) is a concept that involves the relationship between the mean values of request and resistance and does not consider the variability values (Equation 3).

$$SF = \frac{R_{med}}{S_{med}} \qquad \text{Eq. 3}$$

Cintra (2010) and Aoki (2010) presented in Equation 4 the relationship of safety margin, reliability index and overall safety factor, evidencing that these results are statistically independent.

$$SF = 1 + \beta\sqrt{\frac{v_s^2 + v_r^2 - (\beta^2 . v_s^2 . v_r^2)}{1 - (\beta^2 . v_s^2)}} \qquad \text{Eq. 4}$$

Where: β - reliability index; υ_r - resistance coefficient of variation; υ_s - solicitation coefficient of variation.

Cardoso and Fernandes (2001) developed the following mathematical definition for β as a function of the safety factor and of the resistance and solicitation coefficients of variation (Equation 5):

$$\beta = \frac{1 - \frac{1}{SF}}{\sqrt{v_r^2 + (\frac{1}{SF})^2 . v_s^2}} \qquad \text{Eq. 5}$$

Ang and Tang (1984), demonstrated that the probability of failure p_f is a direct function of reliability index β and can be expressed by Equation 6:

$$p_f = 1 - \emptyset(\beta) \qquad \text{Eq. 6}$$

Where: $\varphi(\beta)$ – accumulated normal distribution function

The accumulated normal distribution function was obtained through the Excel spreadsheet (see Cintra and Aoki, 2010). It can use excel software to obtain Equation 6 using the DIST function. norm available in the program (Oliveira, 2013).

$$p_f = 1 - \emptyset(\beta) = 1 - \text{NORM. DIST. } (\beta; 0\,; 1; TRUE) \qquad \text{Eq. 7}$$

RESULTS AND DISCUSSIONS

Estimation of bearing capacity of the soil

The bearing capacity of the soil was performed using the semiempirical methods suggested by Aoki-Velloso (1975), Décourt-Quaresma (1978) and Teixeira (1996). For these methods, it was used the results of standard penetration tests number (N_{SPT}).

Due to the great heterogeneity of the soil and the different lengths of the piles, the results of the bearing capacity varied significantly between the methods. Table 1 shows the results obtained for the total resistance (R) and the length of each station used to perform the surveys.

There are some piles with the same length for different values of N_{SPT}. Then, it was made the arithmetic mean of bearing capacity for all piles at each length. Table 2 shows the bearing capacity values of each method in function of the length of the piles.

Table 1 - Estimation bearing capacity of the soil by three methodologies

Piles	lengths (m)	Bearing Capacity (kN)		
		Aoki – Velloso (1975)	Décourt – Quaresma (1978)	Teixeira (1996)
SP-01	17	1512,76	553,08	997,14
SP-02	17	1724,56	609,78	1134,74
SP-03	21	823,76	368,51	588,11
SP-04	14	961,67	369,14	682,35
SP-05	18	1541,28	571,69	1110,24
SP-06	16	1890,44	640,73	1223,34
SP-07	17	981,41	378,25	671,04
SP-08	12	1210,48	441,35	803,93
SP-09	25	1823,54	672,89	1260,09
SP-101	20	1468,89	554,81	919,06
SP-102	22	1488,22	583,00	985,83
SP-103	19	1164,15	505,48	793,57
SP-104	19	1874,40	687,69	1208,26
SP-105	19	1594,19	580,88	974,52
SP-106	19	1738,96	625,33	1061,23
SP-107	14	1824,09	608,06	1112,12
SP-108	14	1765,69	463,07	797,34
SP-109	17	1135,09	428,20	676,70
SP-110	18	1933,07	753,04	1221,45
SP-111	13	1671,10	563,44	991,49
SP-112	13	820,06	279,76	548,99
SP-113	14	1196,78	317,93	838,81

Source: The authors.

Table 2 - Average values of bearing capacity as a function of the length of the piles

Length (m)	R_{med} (kN)		
	Aoki – Velloso (1975)	**Décourt – Quaresma (1978)**	**Teixeira (1996)**
12	1210,48	441,35	803,93
13	1245,58	421,60	770,24
14	1437,06	439,55	857,65
16	1890,44	640,73	1223,34
17	1338,46	492,33	869,91
18	1737,18	662,37	1165,85
19	1592,92	599,85	1009,39
20	1468,89	554,81	919,86
21	823,76	368,51	588,11
22	1488,22	583,00	985,83
25	1823,54	672,89	1260,09

Source: The authors.

Statistical analysis of request and resistance results

Table 3 presents the statistical results for the Aoki-Velloso (1975), Décourt-Quaresma (1978) and Teixeira (1996) methods.

The load values transferred to the foundation elements determined by Alves (2021) are shown in Table 4, as well as the percentage of load transferred for each model analyzed.

Table 3 - Statistical analysis of resistance values

L (m)	**Aoki-Velloso (1975)**				**Décourt-Quaresma (1978)**				**Teixeira (1996)**			
	$R_{méd}$ (kN)	σ_r (kN)	v_r	v_r (%)	$R_{méd}$ (kN)	σ_r (kN)	v_r	v_r (%)	$R_{méd}$ (kN)	σ_r (kN)	v_r	v_r (%)
12	1210,48	0	0	0	441,4	0	0	0	803,93	0	0	0
13	1245,58	601,8	0,483	48,31	421,6	200,6	0,476	47,58	770,24	312,9	0,406	40,62
14	1437,06	424,9	0,296	29,56	439,5	127,4	0,29	28,99	857,65	182,10	0,212	21,23
16	1890,44	0	0	0	640,7	0	0	0	1223,3	0		0
17	1338,46	340,7	0,254	25,46	492,3	107,4	0,218	21,82	869,9	233,2	0,268	26,81
18	1737,18	277,0	0,160	15,95	662,4	128,2	0,194	19,36	1165,8	78,64	0,067	6,75
19	1592,92	307,9	0,193	19,33	599,8	76,7	0,128	12,78	1009,4	173,2	0,172	17,16
20	1468,89	0	0	0	554,8	0	0	0	919,9	0	0	0
21	823,76	0	0	0	368,5	0	0	0	588,1	0	0	0
22	1488,22	0	0	0	583,0	0	0	0	985,8	0	0	0
25	1823,54	0	0	0	672,9	0	0	0	1260,1	0	0	0

Source: The authors.

Table 4 - Load transferred by foundation element

SCENARIOS		**TRANSFERRED LOAD (kN) / % TRANSFERRED LOAD**			
Nº	**Descrição dos apoios**	**PILES**		**RAFT**	
1	Rigid in the piles Free raft	30879,07	100	0	0
2	Rigid in the piles Springs in the raft (k_{ms} = 259,28 kN·m⁻¹·knot)	30454,91	98,63	424,16	1,37

Source: adapted from Alves, 2021

For the probabilistic analysis of the two models, in all piles the mean values and standard deviations determined by Alves (2021) were used, as shown in

Table 5, since it is not possible to precisely determine the exact request in each station.

Table 5 - Analysis of load dispersion in piles

MODEL	Loading (kN)			SPREAD	VARIANCE	Standard deviation (kPa)
	MIN	MED	MAX			
1	120,15	376,57	606,3	486,15	8033,01	89,63
2	117,93	371,40	596,31	478,38	7738,36	87,97

Source: adapted from Alves, 2021

As the same request value is being considered in the analyzed piles (376.57 kN and 371.40 kN), Aoki and Velloso (1975) suggest that a minimum coefficient of variation of 10% be adopted by the distribution of loads in the piles not being homogeneous. However, as the standard deviation of each model is known, the coefficient of variation can be obtained by Equation (2). Table 6 presents the statistical analysis of the request values for the two models.

PROBABILISTIC ANALYSIS OF PROBABILITY DENSITY RESULTS AND CURVES

Due to the existence of variability in both the request and the resistance, it is possible to perform a statistical approach and determine the curves of the probability density functions for both the resistances and the request for both models.

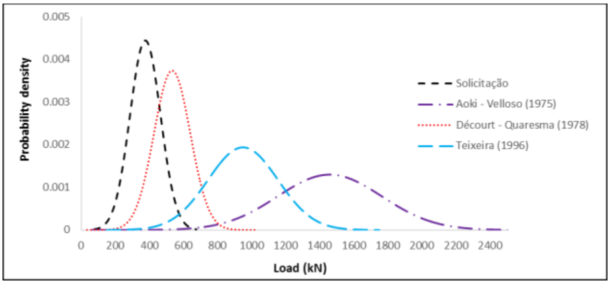
Figure 6 and Figure 7 include, respectively, the probability density curves for Model 1 and Model 2 are presented. Analyzing the graphs of both models, it is note that the higher the slope and the lower the convolution of the curve, the greater the probability that the resistance tends to the average resistance value. For both models, it is possible to notice that the curve associated with the Décourt-Quaresma method (1978) has a higher probability density when compared to the other methods adopted in the research.

Table 6 - Statistical analysis of the request values for Model 1 and Model 2.

L (m)	MODEL 1					MODEL 2				
	Solicitation (kN)	S_{med} (kN)	σ_s (kN)	v_s	vs (%)	Solicitation (kN)	S_{med} (kN)	σ_s (kN)	vs	vs (%)
12 a 25	376,57	376,57	89,63	0,2380	23,80	371,40	371,40	87,97	0,2368	23,68

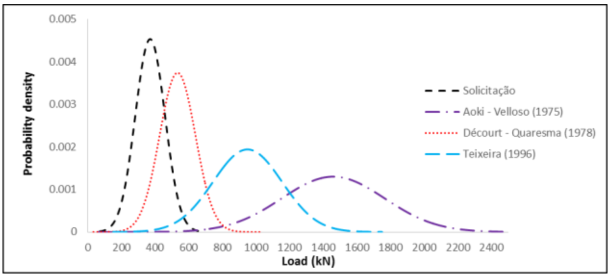
Source: The authors.

Figure 6. Probability density curves - Model 1



Source: The authors.

Figure 7. Probability density curves - Model 2



Source: The authors.

ANALYSIS OF RELIABILITY RESULTS AND PROBABILITY OF FAILURE

For the determination of the probability of failure it is important to determine the mean safety margin (z_m), which is the difference between the average resistance of the soil and the resistance value requested by the pile.

Table 6 and Table 7 show, respectively, the values of probability of failure and reliability referring to Model 1 and Model 2. In both models, the Décourt-Quaresma method (1978) presented the lowest z_m value, indicating that it has a lower safety margin compared to the other methods and consequently has the lowest safety factor. Therefore, the Décourt-Quaresma method (1978) is the one with the highest probability of ruin.

Table 6. Probability of failure and reliability values - Model 1

Method	σz (kN)	Zm (kN)	FS	β	pf	1/pf
Aoki – Velloso (1975)	319,606	1083,11	3,876	3,389	0,00035086	2850,14
Décourt – Quaresma (1978)	139,257	157,70	1,419	1,132	0,12872403	7,77
Teixeira (1996)	224,293	573,81	2,524	2,558	0,005259	190,15

Source: The authors.

Table 7 - Probability of failure and reliability values - Model 2

Method	σz (kN)	Zm (kN)	FS	β	pf	1/pf
Aoki – Velloso (1975)	319,144	1088,28	3,930	3,410	0,00032481	3078,76
Décourt – Quaresma (1978)	138,194	162,87	1,439	1,179	0,11928633	8,38
Teixeira (1996)	223,634	578,98	2,559	2,589	0,00481325	207,76

Source: The authors.

To evaluate the reliability of the project, the probability of failure following the proportionality presented in Table 8 is based on the reliability of the project, thus noting the risk and time of recurrence considering the recommendation of the MIL-STD-882 standard (Santos, 2021).

Table 8 - Subjective risk scale and recurrence time considering the recommendation of the MIL - STD - 882 (Clemens, 1983) expanded standard and cited by Aoki (2011).

β	Occurrence	Occurrence time	Frequency	Level	Probability level	pf
-7,94	certain	1 day	every day		1	1
0	50% probability	2 days	every 2 days		$2x10^{0}$	0,5
0,52	frequent	1 week	every week	A	$3x10^{-1}$	0,3
1,88	probable	1 month	every month	B	$3x10^{-2}$	0,03
2,75	occasional	1 year	every year	C	$3x10^{-3}$	0,003
3,43	remote	10 years	every decade	D	$3x10^{-4}$	0,0003
4,01	Extremely remote	100 years	every century	E	$3x10^{-5}$	0,00003
4,53	impossible in practice	1000 years	every millennium		$3x10^{-6}$	$3x10^{-6}$
7,27	never	5,48 $x10^{+12}$ years	age of the universe		0	$1{,}83x^{-13}$

Source: Santos (2021)

According to Meyerhof (1995, apud Cardoso and Fernandes (2001)) the probability of failure linked to foundation projects should be between 0.0004 (1/2,500) and 0.0001 (1/10,000). Eurocode EN (1990), another criterion for the analysis of probability of failure shows that the standards set out in the European Code are:

- In small work (RC1), the limit probability is 1/2,069;
- In commercial works (RC2), the limit is 1/13,822 and;
- In large works (RC3) the probability should be 1/117,096.

Recurrence time and frequency represent a correlation between the estimated value for the reliability index and the time of probable occurrence of a pile rupture in days, weeks, months, or years. It represents, therefore, a more intuitive way of interpreting the degree of risk to which the work is inserted, thus helping the laity to interpret the results (Oliveira, 2018).

The evaluation of the values of the probability of failure for Model 1 indicate that one in every 2850 piles will reach the condition of collapse/rupture according to the Aoki-Velloso method (1975), with a reliability index (β) equal to 3.389. As the enterprise has 1490, none should reach the failure condition. These values meet the parameters established by the European code for the RC1 criterion, besides being within the range established by Meyerhof (1995), in which the risk considered of the enterprise is considered acceptable.

Analyzing Teixeira's method (1996), one in every 190 piles will reach the breaking condition, with a reliability index of 2.558. Considering the number of piles used at least 7 piles should reach the condition of collapse. The Décourt-Quaresma method (1978) is even more critical since one in every 7 piles will reach ruin condition, with a reliability index of 1.132, indicating that at least 191 of the 1490 piles used will collapse. Both Teixeira's (1996) and Décourt-Quaresma's (1978) method do not meet the recommendation established by the European code, nor the criteria established by Meyerhof (1995). That is, the risk considered for these methods is not acceptable.

According to the subjective scale of risk and recurrence time according to the recommendation of the MIL-STD-882 standard (Table 8), Model 1 has the following classification:

- The Aoki-Velloso method (1975) (ß = 3.389) presents an occasional occurrence of failure.
- The Décourt-Quaresma method (1978) (ß = 1.132) presents a frequent occurrence of failure.
- The Teixeira method (1996) (ß = 2.558) presents a probable occurrence of failure.

The evaluation of the values of the probability of failure for Model 2, indicate that one in every 3078 piles will reach the condition of collapse/rupture according to the Aoki-Velloso method (1975), with a reliability index (ß) equal to 3.410. As the enterprise has 1490, none should reach the condition of ruin. These values meet the parameters established by the European code for the RC1 criterion, besides being within the range established by Meyerhof (1995), in which the risk considered of the enterprise is considered acceptable.

Analyzing Teixeira's method (1996), one in every 207 piles will reach the breaking condition, with a reliability index of 2.589. Considering the number of piles used approximately 7 piles should reach the collapse condition. The Décourt-Quaresma method (1978), as well as Model 1, was the method that presented the most critical condition since one in every 8 piles will reach the condition of failure, with a reliability index of 1.132, indicating that at least 186 of the 1490 piles used will collapse. Both Teixeira's (1996) and Décourt-Quaresma's (1978) method do not meet the recommendation established by the European code, nor the criteria established by Meyerhof (1995). That is, the risk considered for these methods is not acceptable.

According to the subjective scale of risk and recurrence time according to the recommendation of the MIL-STD-882 standard (Table 8), Model 2 has the following classification:

• The Aoki-Velloso method (1975) (ß = 3.410) presents an occasional occurrence of failure.

• The Décourt-Quaresma method (1978) (ß = 1.179) presents a frequent occurrence of failure.

• The Teixeira method (1996) (ß = 2.589) presents a probable occurrence of ruin.

In both models, the Décourt-Quaresma method (1978) presented very different load estimation values than the values proposed by the Aoki-Velloso (1975) and Teixeira (1996) methods. This is due to the achievement of lateral resistance, since the Décourt-Quaresma method (1978) does not separate the Nspt by the soil layer but considers the soil consisting of a single layer with medium Nspt, disregarding the value of the tip and above the tip of the pile. This consideration of the method ends up interfering in the criteria of probability of failure since the methodology of Décourt-Quaresma (1978) ends up acquiring a low reliability index (ß) when compared to the other methods.

CONCLUSION / FINAL CONSIDERATIONS

The main findings of the article are listed below:

• The method suggested by Aoki-Velloso (1975) presents the greatest variation in the load capacity estimation values in both models. However, even though the method presented the highest dispersion in the data, it has the highest reliability index and the lowest probability of ruin due to its high safety factor (FS).

• The method suggested by Décourt-Quaresma (1978) presents the smallest variation in the load capacity estimation values in both models and therefore the values obtained are very close to the average. However, this method has the lowest reliability index, the highest probability of ruin and consequently the lowest safety factor (FS).

• The method suggested by Teixeira (1996) presents greater variation in load capacity results than the method suggested by Décourt-Quaresma (1978) and less variation than the method suggested by Aoki-Velloso (1975).

• The value of the probability of failure is directly associated with the semiempirical method used, which causes a great variability in the results.

• Verifying the Meyerhof criteria (1995) and the requirements established by the European code, it can be stated that for the work in question, only the method suggested by Aoki-Velloso (1975) meets the imposed requirements, making the risk acceptable with an occasional occurrence of failure.

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