Failure load analysis methods based on instrumented large diameter bored pile load tests

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ABSTRACT
This paper presents an evaluation of the results (load versus settlement curve) of three instrumented load tests, performed on large diameter bored piles, through some extrapolation methods of failure load. The load tests were performed on three instrumented piles of 1.20 m in diameter and lengths between 20 and 30m, with the use of excavated mud stabilizer (bentonite). Methods of extrapolation of the failure load used are characterized by using information of the tests and the geometric characteristics of the piles. The methods are: Method of stiffness Décourt (1996), Method Davisson (1972), Method of ISO 6122 (2010), Method of Brinch-Hansen 80%, Method Kondner-Chin (1970, 1971), Method Van der Veen (1953), Method Mazurkiewicz (1972), Method of Butler & Roy (1977) and Method of De Beer (1968). Analyses show the applicability of the extrapolation methods of failure load for the results of instrumented load test of large diameter in typical geological horizon of the Tertiary sediments of the sedimentary basin of São Paulo, Brazil, with intercalations of clay and sandy soil.

RESUMO
O presente trabalho apresenta a avaliação dos resultados (curva carga vs recalque) de três provas de carga instrumentadas, realizada em estacas escavadas de grande diâmetro, através de alguns métodos de extrapolação da carga de ruptura. As provas de carga instrumentadas foram realizadas em 3 estacas de 1,20m de diâmetro e comprimentos entre 20 e 30m, escavadas com o uso de lama estabilizante (bentonita). Os métodos de extrapolação da carga última utilizados caracterizam-se por usarem, tanto informações dos ensaios, quanto das características geométricas das estacas. Os métodos utilizados são: Método da Rigidez de Décourt (1996), Método de Davisson (1972), Método da NBR 6122 (2010), Método de Brinch-Hansen 80%, Método de Chin-Kondner (1970, 1971), Método de Van der Veen (1953), Método de Mazurkiewicz (1972), Método de Butler & Roy (1977) e o Método de De Beer (1968). As análises mostram a aplicabilidade dos métodos de extrapolação da carga de ruptura para os resultados da prova de carga instrumentada de grande diâmetro em horizonte geológico típico de sedimentos de período terciário da Bacia Sedimentar de São Paulo, Brazil, com intercalações de solo argilo e arenoso.

1 INTRODUCTION

This paper presents an evaluation of three instrumented load tests performed on large diameter bored piles. The tested piles are part of the retailer Mall Union buildings foundations, located in Osasco city, in the western part of São Paulo´s metropolitan region, Brazil.

The load tests followed the Brazilian Standard NBR 12131/2006 - Static Load Tests recommendations, using slow loading and fast unloading. Geologically, the region in which the piles are inserted is a sedimentary basin, known as the São Paulo tertiary sedimentary basin, more specifically Resende Formation, with intercalations of silty clay and gray purple and yellow sand layers.

The piles have circular cross-section, with a 1.20m nominal diameter, 23m, 29m and 31m lengths and were built with the aid of stabilizing mud (bentonite slurry). Pile instrumentation was done with strain gages, which were fixed directly on the pile reinforcement rebars and placed at seven pre-defined elevations along the pile.

The used ultimate load extrapolation methods are: Method of stiffness Décourt (1996), Method Davisson (1972), Method of Brazilian Standard - NBR 6122 (2010), Method of Brinch-Hansen 80% (1963), Chin-Kondner Method (1970, 1971) Method, Van der Veen (1953), Method Mazurkiewicz (1972), Method of Butler & Roy (1977) and Method of De Beer (1968).

2 DESIGN

The tested piles are part of the retailer Mall Union buildings foundations, located in Osasco city, in the western part of São Paulo´s metropolitan region, Brazil.

The foundations of the buildings were set on the project as being bored piles with the aid of mechanical action of stabilizing mud (bentonite slurry).

The tested piles chosen for the test loads have circular cross-section of 1.20 m in diameter and nominal effective length between 23 and 31m.

The load tests were performed with loading and unloading of the slow type type fast.

The instrumentation of the pile was done with resistance strain gages (strain-gages). The vertical displacements (settlements) in the pile were measured using four deflections positioned two by two, diametrically opposed.

Table 1 shows the data of the tested piles, such as identification, diameter, length, elevation and peak workload for them.

Table 1. Characteristics of tested piles.

Piles	D (m)	L (m)	Botton	N (kN)	Levels Instr.
E.263b	1,20	23	722,30	2800	7
E.113	1,20	29	714,36	4427	7
E.25	1,20	31	713,86	5650	7

The reaction system of load test consisted of a metal shell anchored on the ground by 12 rods of steel wire ropes 190 CP RB, with a total length of 30m, 10m and anchored to the maximum load in the test of 150tf in each truss. The above description can be viewed in a photo 1

Foto 1 – Reaction system.

It should be noted that in the first trial (E.263b stake), there was a problem in the hydraulic system of pumps, which prevented the continuation of the load test, but after the repair was made a new load, type faster, until the level reached prior to the problem. From that point, the loading proceeded slowly.

During assembly of the first test, it was found that on two anchor, one strand was shorter and can not be prestressed along with the other by hydraulic jack, limiting the load of risers to the equivalent of 11 ropes. In the third test at three separate rods, one strand was broken and others were sheeted, and load shedding was identical to the first load test.

3 SITE GEOLOGY

To the knowledge of the subsoil of the site where the work was perfomed out a major campaign to geotechnical investigation, using the percussion drilling sampled using standard (standard penetration test - SPT) in the entire region.

Regionally, the region, in which the inserted piles, is a sedimentary basin soil, known as the Tertiary sediments of the Basin of São Paulo, more specifically Resende Formation.

The campaign of investigation (standart penetration teste - SPT) showed a typical entanglement between silty clay and gray sand purple and yellow, with consistency and compactness, respectively high, as Figure 1.

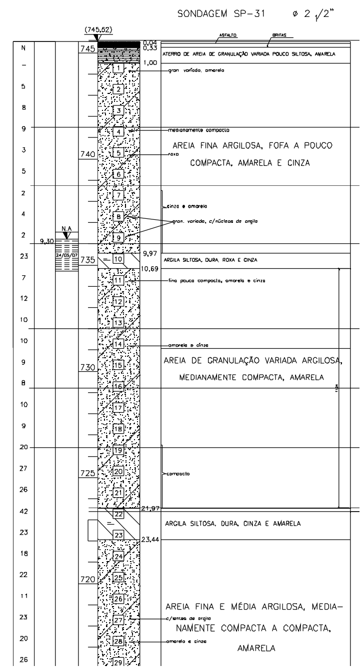

Figure 1 – Standart penetration test of representative of the site.

The fundamental characteristics of the soils belonging to this formation are the homogeneity and the fact that they are little affected by weathering processes and hemispheric dominance.

4 FUNDAMENTAÇÃO TEÓRICA

The methods that will be addressed in this work are the five methods outlined Fellenius (2001), which are: Davisson (1972), De Beer (1968), Brinch-Hansen 80% (1963), Chin-Kondner (1970, 1971 - proposed change in the work of Kondner (1963)) and Décourt (1996). Also shown are the methods of Van der Veen (1953), Mazurkiewcz (1972), Butler & Roy (1977) and the Brazilian standard of foundations (1996). Besides these methods will be studied relations modified Cambefort (1964) and the Method of Two Lines, the second Massad and Lazo (1998).

Below are summarized as descriptions of each method.

4.1 Method of Stiffness (Dècourt, 1996)

The method proposed by Décourt (1996), known as method of stiffness, uses the concept of rigidity, which is the ratio between the load applied on top of the pile and its settlement. Thus, one can draw a graph in which the horizontal axis represents the applied load and the vertical axis stiffness, defining two types of rupture: Physics (zero stiffness) and Conventional (upsetting the top 10% larger than the diameter).

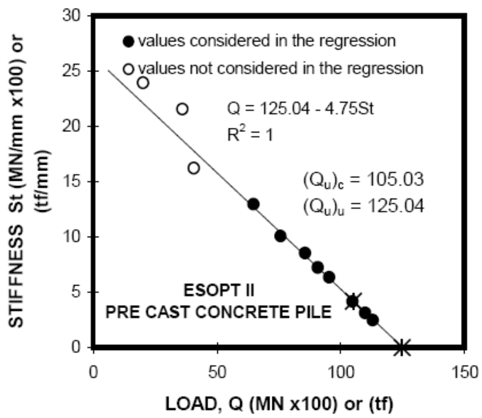

Figure 2 – Exemple of conventional and physics ruptures on the pre-shaped piles (Décourt, 2008).

4.2 Method of Chin-Kondner (1963; 1970; 1971)

The method proposed by Chin (1970, 1971), in a study based on work by Kondner (1963), allows the extrapolation of the failure load in the static load tests. The method consists of dividing each respective load applied by the settlements and put it in the y-axis. In turn, the x-axis, places the settlements obtained during the static load test. The load limit is given by the inverse of the slope formed by the points plotted on the graph.

4.3 Method of Davisson (1972)

The method proposed by Davisson (1972), known as Offset Limit, assumes that the load limit is given by an equation dependent on the diameter of the pile and above the elastic compression of the pile in 4mm.

$$\rho = (4 + \frac{b}{120}) + \frac{Q.L}{E.S} \qquad (1)$$

ρ = Stresses for to one given load applied [mm];
b = Diameter of the prop [mm];
L = Length of the prop [mm];
Q = Applied Load [km];
E = Young's modulus of the prop [kN/m ²];
S = Area of the Transversal Section of the prop [m ²]

4.4 Method Based on Modified Cambefort Relations

The laws or relationships Cambefort explain what is already enshrined in technical area. The figure 3 shows that it takes a few mm (y1) for the lateral friction is completely exhausted, while that to reach the break of the base is needed to achieve shifts much higher (y2).

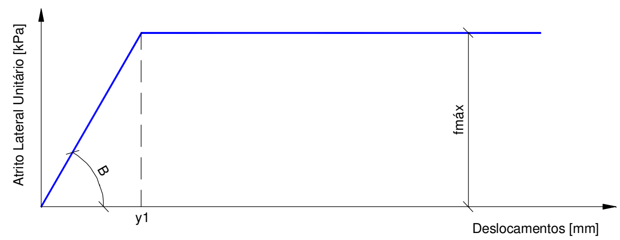

Figure 3 - 1st Cambefort Ratio (Cambefort, 1964).

4.5 Method of Two Lines

The method of the two lines proposed by Massad and Lazo (1998), applies specifically to the piles classified as rigid or short. This classification is based on an equation in which k ≥ 8 indicates a long pile or compressible, which is the need to deform much so that there is a depletion of lateral friction. In turn, if the result is k ≤ 2 the situation is tight, or short pile, for which the skin friction is almost sold out instantly.

$$k = \frac{Q_{L_{RUP}}}{K_r . y_1} \qquad (2)$$

4.6 Method of the Brazilian Standard (NBR 6122/1996)

The method of NBR 6122 is based on the concepts of the method of Davisson (1972), by changing the amount paid to offset initial plastic.

$$\rho = \frac{D}{30} + \frac{Q.L}{E.S} \qquad (3)$$

4.7 Method of Brinch-Hansen 80% (1963)

The method calculates the square root of settlements and divide them by their loads, putting this relationship in the y-axis. In turn, the x-axis, place the settlements obtained during the static load test.

4.8 Method of De Beer (1968)

The method proposed by De Beer (apud Fellenius) allows to find the breaking load by plotting a graph in which the logarithm of the load is placed on the ordinate axis while the abscissa axis, the logarithm of repression.

4.9 Méethod of Van der Veen (1953)

The method suggests that the relationship between load and displacement at the top presents an aspect exponentially.

4.10 Method of Mazurkiewicz (1972)

Mazurkiewicz (1972) suggested a method of extrapolating the curve of load vs settlement, assuming the same as a parable. Thus, the method proposed horizontal parallel lines with distance H between them, intercepting the curve, then vertical lines are drawn, starting from each point of intersection to the x-axis, corresponding to the loads at the top. Line segments to 45° are plotted, each with ends at the point of intersection of the x-axis and the vertical parallel line next. Finally, the line passing through the intersections of the segments with the vertical as it crosses the horizontal axis indicates the breaking load.

5 ANALYSIS AND RESULTS

5.1 Method of Stiffness (1996)

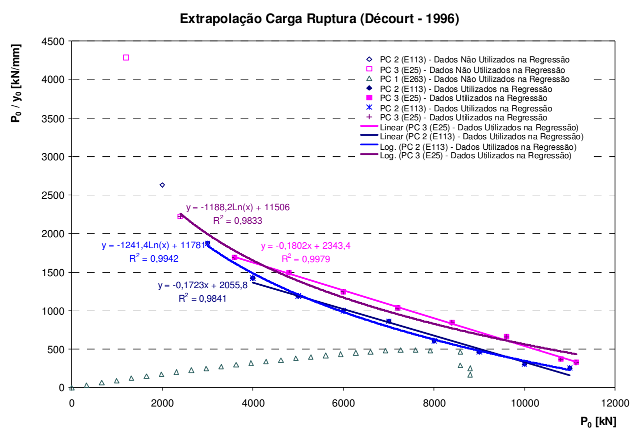

Figure 4. Stiffness Method by Décourt

In this method, the author asserts that the displacement pile's reach the conventional rupture and the physical rupture (linear regression), which means the one related to the null stiffness; on the other hand, drilled pile's and shallow footing hardly show physical rupture, but only conventional rupture, related to a 10% settlement of the pile's diameter (logarithmic regression). However, what can be seen in Figure 4 is that the piles presented both conventional rupture and physical rupture. The PC.2, represented by the dark blue / blue colors, the correlation ratio (R^2) resulted is closer to one by using logarithmic regression. Unlike PC.2, PC.3 represented by the purple / pink colors, the correlation ration resulted is closer to one by using linear regression. Due to the many loads on PC.1, the method didn't apply correctly, fact already alerted by the author in one of his lectures at the IE and can be proved by Massad (2008). The failure loads for both linear and logarithmic regression are listed in table 2.

	Qu [kN]	
	Linear	Logarithmic
PC1	Not aplicable	
PC2	11931,51	13228,01
PC3	13004,44	16051,45

Table 2. Values of Failure Loads by Stiffness Method.

	Qu [kN]	
	Linear	Logarithmic
PC1	Not aplicable	
PC2	11931,51	13228,01
PC3	13004,44	16051,45

5.2 Method of Chin-Kondner (1963; 1970 e 1971)

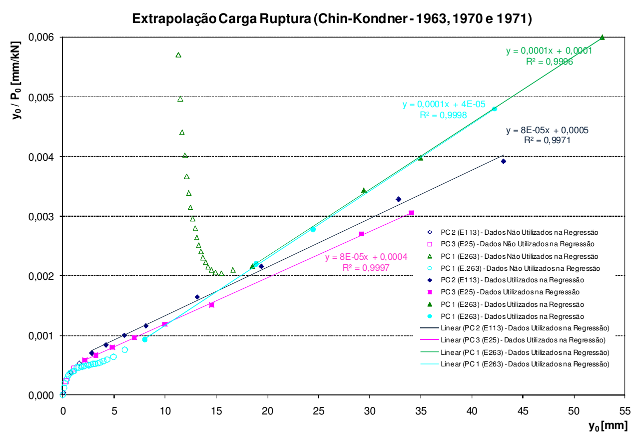

Figure 5. Chin-Kondner Method

For the load tests 02 and 03, PC.02 and PC.03, it was possible to apply the method proposed by these authors. However for PC.1, in which there were two loading steps, the curve form didn't adjust to the suggested method, as can be seen by the dots represented by green color. Even so, just for curiosity, the displacement was nulled and the result is exposed in the graphic by the cyan color. With that, the graphic shape could be showed as the others. The failure load values are indicated in table 3Table .

Table 3. Values of Failure Loads by Chin-Kondner Method.

			Zeroing the displacement at 10.5 mm.	
	C1[kN]	Qu[kN]	C1[kN]	Qu[kN]
PC1	1,116E-04	8956,66	1,126E-04	8877,31
PC2	8,121E-05	12313,53		
PC3	7,755E-05	12895,68		

5.3 Method of Davisson (1972)

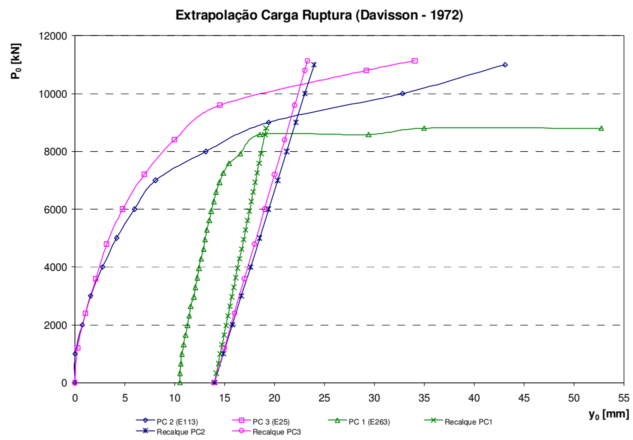

Figure 6. Davisson Method

The Davisson method could be applied to the three loading tests, but presented lower values when compared to the two other methods mentioned before. As the three piles have the same diameter, the registered offset was 14mm. The values of the failure load are in table 4.

Table 4. Values of Failure Loads by Davisson Method.

	OFFSET(mm)	Qu[Kn]
PC1	14,00	8600,00
PC2	14,00	9200,00
PC3	14,00	10200,00

5.4 Method of NBR 6122 (1996)

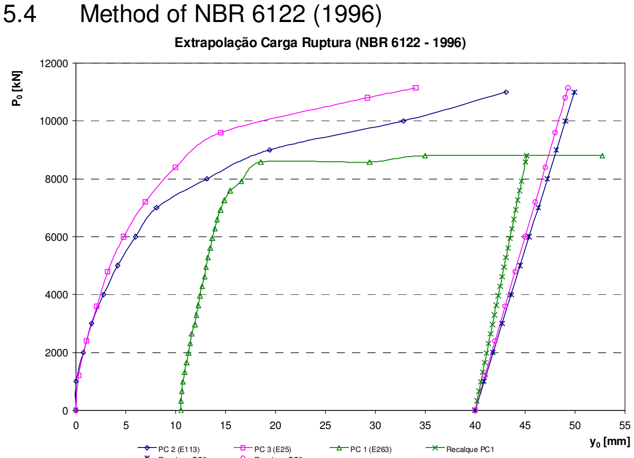

Figure 7. Brazilian Standard Method (NBR 6122)

The method suggested by the Brazilian Standard is very similar to the Davisson method, except by the initial displacement. However, because of the pile diameter, the origin related offset was excessive, overcoming the maximum settlements obtained by static tests, except for the PC.01. In such case, the method doesn't apply.

5.5 Method of Brinch-Hansen 80% (1963)

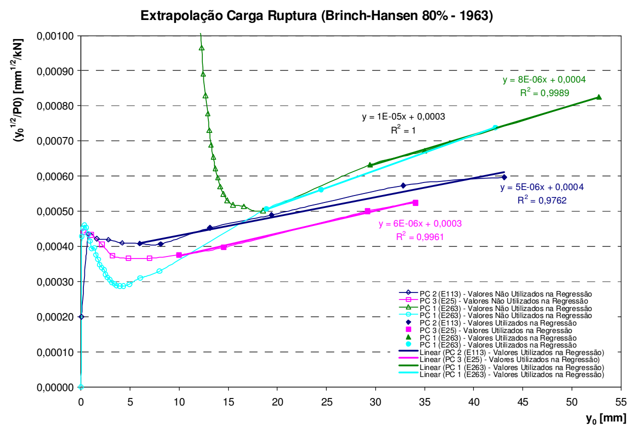

Figure 8. Brinch-Hansen 80% Method.

The method idealized by Hansen provided curves parabolic shaped and, using linear regressions, taking the correlation ratio as a parameter, it was possible to identify the angular and linear coefficients for each curve, resulting in the failure loads showed in table 5.

Table 5. Values of Failure Loads by Brinch-Hansen 80% Method.

zeroing the displacement at 10.5 mm.					
	C1[kN]	C2[kN]	Qu[kN]	C1[kN]	Qu[kN]
PC1	8,360E-06	0,0004	8646,44	9,934E-06	9159,07
PC2	4,974E-06	0,0004	11208,99		
PC3	4,802E-06	0,0003	13173,21		

Observe in figure 8 that the PC.01 shape of the curve (presented in green color) is different than the others, due to the fact of two loading steps. When the first load displacement was nulled, the graphic assumed a similar behavior to the others.

5.6 Method of De Beer (1968)

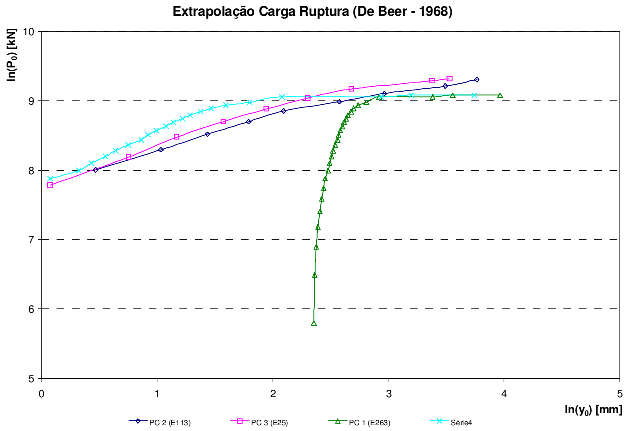

Figure 9. De Beer Method.

This method presented much lower values for the rupture load tests, when compared to the other presented methods. Once again, depending on the loading steps, the PC.01 didn't present the appropriate shape. The displacement annulment was necessary, presented by the cyan curve. The results are in table 6.

Table 6. Values of Failures Loads by De Beer Method.

zeroing the displacement at 10.5 mm.				
	Ln (P0)	Qu[kN]	Ln (P0)	Qu[kN]
PC1	Não aplicável		9,05	8518,54
PC2	8,80	6634,24		
PC3	9,10	8955,29		

5.7 Method of Van der Veen (1953)

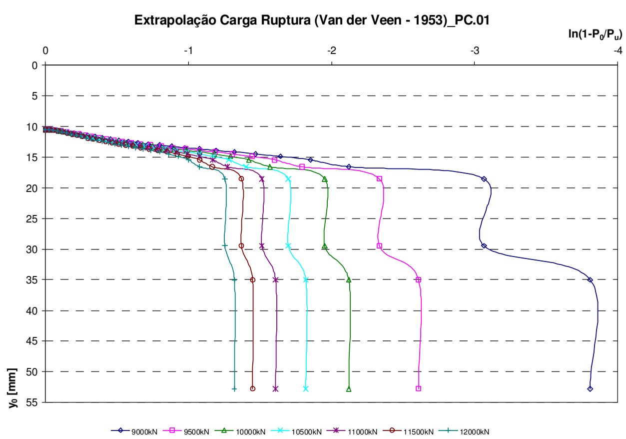

Figure 10. Van der Veen Method_PC.01

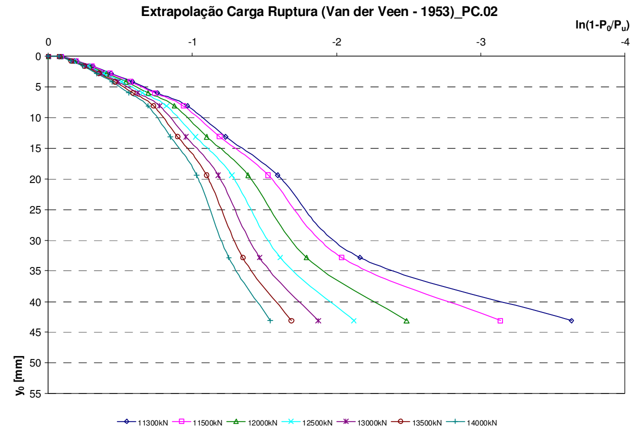

Figure 11. Van der Veen Method – PC.02

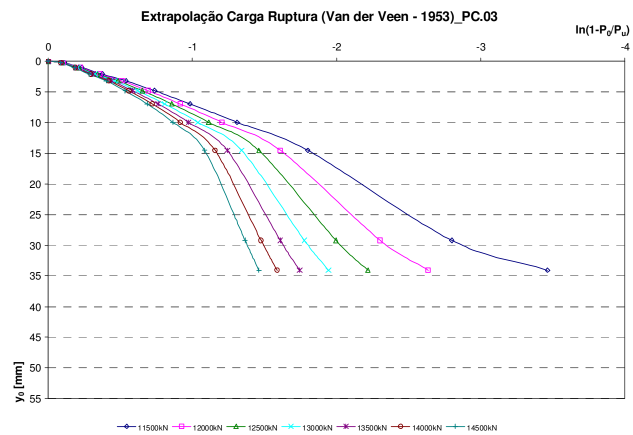

Figure 12. Van der Veen Method – PC.03

The exposed graphics based on the method suggested by Van de Veen, in general, didn't apply well to the kind of pile in question. None of the loading tests presented it was possible to determine a linear relation to represent a rupture load. Observing the graphics, of the figures 10 to 12, it is possible to realize that the method is not suitable for drilled pile's, as describe in Décourt and Nyama (1994), in which it was proven that the application of the method is valid for monotonic loading and displacement piles.

5.8 Method of Mazurkiewicz (1972)

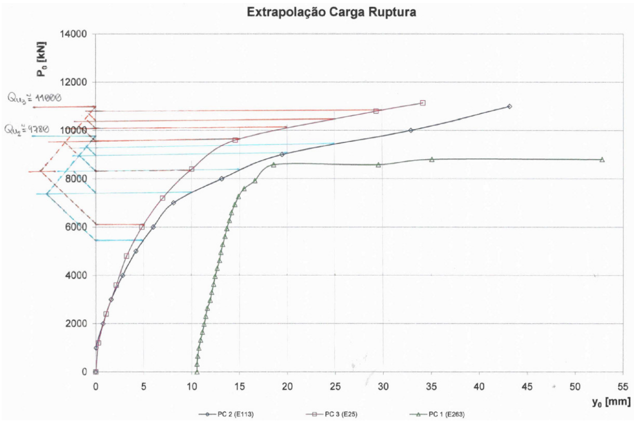

Figure 13. Mazurkiewicz Method.

The method proposed by Mazurkiewicz presented more conservatives results when compared to the previous methods, except for the De Beer method, which showed lower values among all the presented methods.

5.9 Method of Butler & Roy (1977)

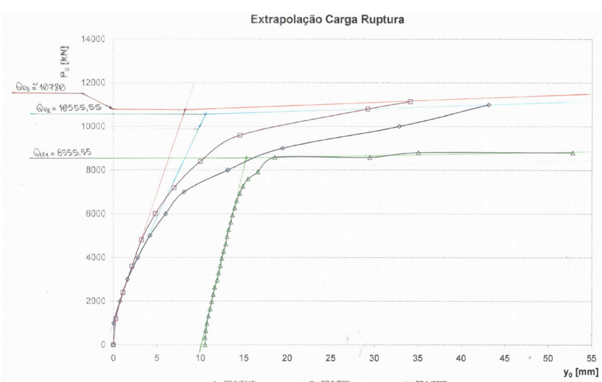

Figure 14. Butler & Roy Method.

This method also didn't present satisfactory results, because the ultimate load was much lower than the expected. The method represented well, as the purpose of comparison, the rupture load for the PC.01, as long as it had reached the rupture.

6 CONCLUSIONS

Table 7 shows the resume of the rupture loads calculated by different extrapolation methods.

Table 7. Summary of Failure Loads.

	PC.01 (E.263b)	PC.02 (E.113)	PC.03 (E.25)
Décourt (1996)	-	13228 kN	13004 kN
Chin-Kondner (1963, 1970 e 1971)	8956 kN 8877 kN[1]	12313 kN	12895 kN
Davisson (1972)	8600 kN	9200 kN	10200 kN
NBR 6122 (1996)	-	-	-
Brinch – Hansen (1963)	8646 kN 9159 kN[1]	11209 kN	13173 kN
De Beer (1968)	8518kN *	6634 kN	8955 kN
Van der Veen (1953)	-	-	-
Mazurkiewicz (1972)	-	9780 kN	11000 kN
Butler & Roy (1977)	-	10555 kN	10780 kN

[1]These values correspond to shifts in PC01 zeroing, due to a problem in hydraulic jacks, which forced the unloading in the load test.

It is noticed that the graphical methods proposed by Mazurkiewicz (1972) and Butler & Roy (1977), as well as the De Beer (1968) method, didn't apply efficiently and the presented results beneath the expectations. The method proposed by Van der Veen is indiscriminately used in technical means, but its validity is restrained to the monotonic loadings, and it's not applicable in this case. The same can be said to the Brazilian Standard Foundation, which is based on the Davisson method. This method, when it is related to large diameters piles, the plastic part of displacement is too large and it would be necessary to achieve very large displacements so that the method was applicable. It's possible to see, by the loading curves VS settlement of the loading tests PC.02 and PC.03 that the piles still have the capability of loading gain, because the friction has not ended up, however, the methods resulted in values that physically don't make any sense.

The methods, in general, have achieved values close to the PC.01 rupture load.

On the other hand, Décourt (1996) and Chin-Kondner (1963, 1970 and 1971) resulted in very close values and also physically consistent values. The piles E.113 and E.25 have practically the same length, thus, it make sense that the rupture load of both are almost the same.

Therefore, the authors agree with Fellenius (2001), which discard some methods and the recommend the extrapolation of the rupture load by Chin-Kondner and Décourt methods.

7 AGRADECIMETNOS

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