International Journal of
Science and Engineering Investigations vol. 10, issue 116, September 2021
Received on September 4, 2021 ISSN: 2251-8843

Comparison over the Accuracy of Ultimate Bearing Capacity Predictions of an Analytical and a Semiempirical Methods

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Abstract -The prediction of load capacity of piles is a theme of great interest to the foundation project and that still presents uncertainties that need more research to be clarified, being found in the literature different proposed methods to solve that problem. The objective of this work was to compare the accuracy of load capacity predictions provided by an analytical method and a semiempirical one. Then, Aoki-Velloso and NavFac DM 7.2 methods were used in the analysis. The results obtained by such methods were compared with respective results of load tests. Based on the results obtained in the present study, it was concluded that the Aoki-Velloso method obtained a better overall performance than the NavFac Dm 7.2 method, which, associated with the fact that it is a simpler and more practical method, corroborates its greater day-to-day use. It is remarkable, however, that it was observed that the two methodologies presented a considerable margin of error in relation to the actual field results.

Keywords- *Ultimate Bearing Capacity, Aoki-Velloso, NavFac DM*

I. Introduction

Foundations are structural elements of great importance in a construction, due to their capacity of transmitting efforts of a given structure to the ground [1,2,3]. During the designing of foundations, it is necessary to meet some basic requirements, such as: acceptable deformations under working conditions, safety regarding soil collapse and safety regarding the collapse of structural elements [4].

To choose the type of foundation suitable for a given construction, the professional responsible for the project will need studies on the characteristics of the soil, the existence of groundwater in the area, the neighboring buildings, the efforts on the foundation and should also take in account the technologies and materials available for the construction of the foundation in that market. When well designed, the foundation represents 3% to 10% of the total cost of the work [5].

In the literature there are several analytical methods of predicting the ultimate bearing capacity of piles, such as Terzaghi’s, Meyerhof's, and Skempton's. There are also semi-empirical methods, such as Aoki-Velloso (1975), Décourt-Quaresma (1978) and Teixeira (1996), which are the most used in Brazil to determine bearing capacity, and which are based on Standard Penetration Test (SPT) results [6].

Currently there are already very practical ways to obtain the results of predictions by different methods, such as using software that allows calculations to be performed quickly and safely. One of the examples of software widely used in foundation calculations is GEO5. Regarding the prediction of pile´s bearing capacity such software promotes great facility to the professional because it allows the calculation by various theoretical methodologies (such as NAVFAC DM 7.2 and Tomlison) and semiempirical (Aoki-Velloso and Décourt-Quaresma).

More recently, several studies have been developed seeking to estimate the load capacity of piles through even more modern tools, such as the use of neural networks, which are designed to improve some factors such as prediction and approximations of functions and can then be applied in the designing of foundations to increase the accuracy of the predictions of foundation bearing capacity [7].

In view of this scenario, it is interesting to perform comparative analyses between different methods to evaluate which one presents the best performance. In this context, the present study aims to perform an analysis to determine the ultimate bearing capacities of precast concrete piles by the NAVFAC DM 7.2 and Aoki-Velloso methods and then to verify which of the two methods provides better accuracy in relation to the actual capacities’ values obtained through load tests.

II. Literature Review

A. *Foundations*

The foundations arise from the need to transmit efforts from the superstructure to the ground where it will be executed [8]. Refer [2] defines foundations as the bottom of a structure that has as main function to transmit the loads from the superstructure to the soil on which it is supported.

When designed correctly, an infrastructure (foundation) transmits the loads from the structure to the ground avoiding excessive settlements or collapses in the soil [2]. Refer [9] explains that even under the effect of loads, the foundations must be designed and executed in order to ensure some minimum conditions, such as: functionality, safety and durability.

Foundations are divided into two main groups: shallow foundations and deep foundations. Shallow foundations are defined as "those in which the load of the structure is transmitted to the supporting ground directly by the foundation." [1].

Refer [10] defines shallow foundations as "foundation elements in which the load is transmitted to the ground by the tensions distributed under the foundation base".

Deep foundations are defined as those that have preponderance of length in relation to the cross section [1]. In this group are included the piles.

A pile is characterized by being "executed entirely by equipment or tools, without, at any stage of its execution, there is a worker's descent" [2]. The materials used can be wood, steel, precast concrete [10].

B. Ultimate Bearing Capacity of Piles

As mentioned above, the soil should present properties that characterize it as an appropriate place for the construction of a foundation, so that it is possible to withstand the loads coming from the superstructure without any rupture and ensuring that the settlements are suitable for the structure. In general, it’s a consensus that pile´s ultimate load capacity is resulted from the sum of the pile point capacity and the skin friction [11,12].

Although there are several analytical methods to estimate the load capacity of a pile, some of these theoretical methods become less accurate due to some uncertainties and difficulties, such as accurately determining soil parameters and drainage conditions for each layer, for example. Due to this scenario, some Brazilian authors such as Aoki-Velloso (1975) and Décourt-Quaresma (1978) proposed semi-empirical methods to predict load capacities from the results of in situ tests like Standard Penetration Test or Cone Penetration Test [6].

C. Aoki-Velloso Method

Refer [6] affirms the load capacity in a pile is defined in this method by equation 1.

$$Q_{rup} = A_p \frac{k.N_{spt}}{F1} + U\sum \frac{\alpha.k.N_{spt}}{F2} \Delta L \quad (1)$$

Where:

Q_{rup}= Ultimate bearing capacity;

A_p = pile´s cross section (m^2);

Δ_L = Layer thickness (m^2);

U = pile´s perimeter;

$K\ and\ \alpha$ = Coefficients related to soil type (table 1);

F_1 and F_2 = Coefficients related to pile´s type (table 2);

N_{spt}= Nvalues of the soil on the tip of the pile.

TABLE I. AOKI-VELLOSO’S “K” E “α” COEFFICIENTS

Soil Tpe	K(kgf/cm^2)	α(%)
Sand	10.00	1.40
Silty Sand	8.00	2.00
Silty clayey sand	7.00	2.40
Clayey sand	6.00	2.80
Clayey silty sand	5.00	3.00
Silt	4.00	3.00
Sandy silt	5.50	2.20
Sandy clayey silt	4.50	2.80
Clayey silt	2.30	3.40
Clayey sandy silt	2.50	3.00
Clay	2.00	6.00
Sandy clay	3.50	240
Sandy silty clay	3.00	2.80
Silt clay	2.20	4.00
Silty Sandy clay	3.30	3.00

Source: Aoki e Velloso (1975)

TABLE II. AOKI VELLOSO´S “F_1” E “F_2” VALUES

Tipo da estaca	F1	F2
Franki	2,50	2F1
Steel	1,75	2F1
Precast concret	1+D/0,80	2F1
Bored	3,00	2F1
FCA	2.0	2F1

Source: Cintra e Aoki (2010)

D. NAVFAC DM 7.2 Method

The calculation of the ultimate load capacity of the pile by the NavF DM 7.2 methodology is performed by means of analysis that provides the strength of the pile base (R_b) and the lateral resistance of the pile (R_s).

The base resistance for non-cohesive soils is given according to equation 2.

$$R_b = \sigma_{efb}.N_q.A_b \quad (2)$$

Where:

σ_{efb}= effective stress at the pile tip

N_q= support capacity factor

A_b= area of pile tip

For cohesive soils, the base resistance is obtained according to equation 3.

$$R_b = 9.C_u.A_b \quad (3)$$

Onde:

C_u= undrained shear resistance of the soil at the pile tip

A_b= pile´s base area

The lateral resistance for non-cohesive soils is calculated as shown in equation 4.

$$R_s = \sum_{j=1}^{n} K_j . \sigma_{ef,j.} tg\delta_j A_{s,j} \quad (4)$$

Where:

K_j = coefficient of horizontal soil stress in the “j” layer;

$\sigma_{ef,j.}$= effective stress in the “j” layer;

δ_j = angle of friction between soil and pile in the “j” layer;

$A_{s,j}$ = area of shaft in contact with soil in the “j” layer.

For cohesive soils, the lateral resistance is determined according to equation 5.

$$R_s = \sum_{j=1}^{n} \alpha_j . C_{u,j} . A_{s,j} \quad (5)$$

Onde:

α_j = adhesion factor in the “j” layer;

$C_{u,j}$= undrained shear resistance of the soil in the “j” layer;

$A_{s,j}$ = area of shaft in contact with soil in the “j” layer

III. MATERIALS AND METHODS

In the present study, different methods of determination of load capacity for precast driven concrete piles were used to verify the accuracy between the methods chosen in relation to real values obtained by means of load tests, and thus identify among those methods which has better performance.

One of the methods chosen in the present study was the semiempirical method of Aoki-Velloso. The other method chosen was NAVFAC DM 7.2 In both cases, ultimate bearing capacities calculations were performed using GEO5 software.

To determine the load capacity of a pile in the software, in the case of the NAVFAC method, the "Pile" module was used, in which initially the "Select settings" function was selected and later the "Standard - EM 1997 - DA2" was chosen. Soon after, the analysis method "Analytical solution" was chosen, and it was determined that it would be evaluated under "Undrained Conditions". Then it was necessary to determine whether the horizontal support capacity would be analyzed by selecting the option "Do not calculate the horizontal load capacity".

In the next step, the "Profile" window was selected where the depths of each soil interface or the thicknesses of each layer are indicated, thus defining the stratigraphic profile.

In the "Soils" window, the soil parameters of each layer are defined to perform the analysis. In this method (NAVFAC DM 7.2) it was necessary to identify whether each soil layer was cohesive or non-cohesive. If considered as a cohesive soil, it is necessary to define the undrained cohesion of the soil in kilopascal (kPa) and the adhesion factor. The adhesion factor is defined according to soil consistency, pile´s material and total cohesion.

If the soil layer is defined as non-cohesive, it requires the introduction of parameters such as surface friction angle, lateral stress coefficient and pile’s installation methodology.

It is noteworthy that the assigned parameters were not directly determined, but estimated through correlations with N-values, which were the information effectively available in the database used. After the required data is added, you selected the "Add" function and then the "Assign" window, which matches the indicated soil and its position in the stratigraphy.

Soon after it was necessary to define the geometry of the station, selecting in the window "Geometry", where data were introduced referring to the diameter, length, material of the pile and its cross section.

In this method it was not necessary to make modifications in the window "Groundwater level + subsoil", because it has already been defined as a permanent project situation. Finally, the "Vertical capacity" window displays the result of the bearing capacity calculated by the program.

For the second method used in this study (Aoki-Velloso) the module "CPT Pile" was used, in which initially it was necessary to select the "Settings" window, the "Select settings" function and the "Standard - EM 1997" option. Subsequently, the function "SPT" and the type of analysis "Aoki-Velloso" were selected. After selecting the "SPT" window and the "Add SPT" function, the N-values were entered at each meter.

After creating the stratigraphic profile in a similar way to that described for the previous method, the following steps were to fulfill the "Soils" window (in which the soil types are defined from the list presented by the program itself) and then the "Assign" window, to indicate the position of each soil type in the previously defined stratigraphic profile.

Then again it was necessary to select the function "Geometry" to determine the dimensions and characteristics of the pile. Finally, the software presents the result of the ultimate load capacity estimated by the method for that situation through the "Load capacity" window.

Subsequently, comparative analyses were performed in relation to the results obtained by the methods described above, verifying the accuracy between these distinct methodologies in relation to the actual load test results. To verify the quality of the predictions, the following statistical measures were used: error, percentage error, mean percentage error, correlation and mean quadratic error.

Refer [13] explains the absolute error of a measure is defined as the difference between the measured value and the true value of a given magnitude, as shown in equation 6:

$$E = X - X_v \quad (6)$$

Where:

E = absolute error;

X = Measured value;

Xv = True value

In turn, the percentage error is an non-dimensional measure that expresses by percentage the difference between the estimated value and the actual value, and can be defined as shown below in equation 7:

$$Er = \frac{E}{Xv} \text{ x } 100 \tag{7}$$

Mean square error is a measure often used to understand the adaptation of a prediction method to the data and measure the performance of the predictions generated. In general, it is a good criterion for measuring the performance of forecasts [14]. This criterion is usually used to compare prediction methods, because it demonstrates which model minimizes large errors since it shows errors more than other criteria [15].

The root mean squared error (equation 9) is generally used to express the accuracy of numerical results by presenting error values in the same dimensions as the analyzed variable and is defined by:

$$\text{RMSE} = \frac{100}{\overline{\text{V}}} \sqrt{\frac{\sum_{i=1}^{n}(V_i - \overline{V}_i)^2}{n}} \tag{8}$$

Where $\overline{\text{V}}$ is the average of the total results and n the number of observations.

The correlation (equation 9) identifies two groups with a certain relationship with each other, that is, whether the high values of one of the variables are intertwined in high values of another variable, providing a certain value that summarizes the degree of linear relationship [16].

$$\rho \frac{\text{Cov(X,Y)}}{\sqrt{\text{Var(x)Var(y)}}} \tag{9}$$

Where X and Y are the compared variables.

This research used 48 actual field data that provided essential information so that it was possible to estimate the ultimate bearing capacity of a foundation, such as: the stratigraphic profile with soil type, the N-values at each meter, the diameter and length of the pile. The database used was composed of piles that represent part of the database presented by [17] using as reference for real ultimate bearing capacity of each pile in the field the values calculated by the same author from the respective load tests.

IV. RESULTS

The following are the results obtained with the use of GEO5 software to verify the load capacity of the piles.

A. *Aoki-Velloso and NavFac DM 7.2 Methods*

Soon after performing the entire process of entering data in the software, the load capacities for each of the piles were verified. For Aoki-Velloso should be highlighted the insertion of the values of F1 and F2 that can be assigned automatically by the software or specified by the user. In the first simulation, these factors were inserted by the user himself according to the suggestion already presented in table 2 that indicates the values of F1 and F2 for each pile case, depending on its diameter. In a second simulation the factors were automatically added by the software with fixed values (1.2 for F1 and 2.3 for F2), regardless of the pile´s diameter.

In the NavFac DM 7.2 method, the load capacity was verified by inserting the soil parameters. It is emphasized that for the first simulation that was assigned Kdc=1, a value that the software already automatically adopts. Later in the second simulation, the soil parameters were introduced, but with the assignment of Kdc=10, as suggested by [18]. Soon after, the error, percentage error, mean percentage error, correlation and mean quadratic error were verified, which are presented in table 3. Subsequently, it was identified which piles presented errors within margins of up to 10% and up to 20% through the percentage error. Finally, it was verified which piles presented conservative predictions (presenting an estimated value lower than the value verified from the load test).

TABLE III. STATISTICAL RESULTS OBTAINED FOR EACH METHOD

	Aoki-Velloso		NavFac DM 7.2	
	F1and F2 manually added	F1 and F2 automatically added	Kdc=1	Kdc=10
Mean Percentage Error	45.19	49.09	54.48	53.67
Correlation	0.7999	0.7932	0.7601	0.7840
RMSE	994.69	1560.22	2341.84	2520.14
Up to 10 % errors	4 of 48	7 of 48	7 of 48	6 of 48
Up to 20% errors	12 of 48	16 of 48	11 of 48	10 of 48
Conservative cases	37 of 48	35 of 48	41 of 48	39 of 48

At first it was found that the Aoki-Velloso methodology (using F1 and F2 values suggested in literature) obtained the best results in terms of the percentage error and in the root mean squared and the correlation. Referring to quantity of piles with results with a margin of error of 10% and 20% the Aoki-Velloso (with automatic F1 and F2) method obtained however, it is worth mentioning that NavFac (using Kdc=1) obtained the same number of piles with a margin of error of up to 10%. It is also notable that all methods present conservative values for most results.

Soon after, a scatter plot was elaborated (Fig. 1) for the results obtained with the Aoki-Velloso method with the values of F1 and F2 manually inserted.

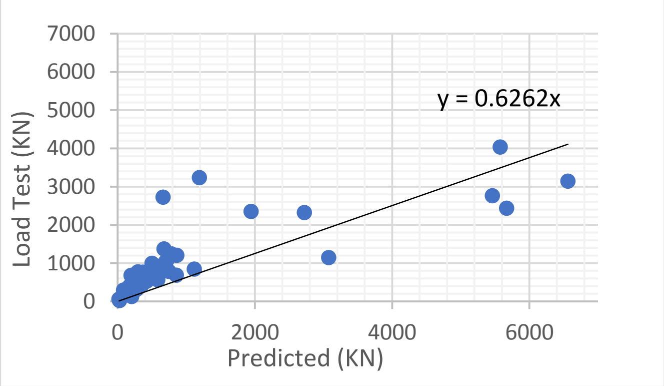

Figure 1. Scatter plot for F1 and F2 inserted manually. Source: Authors.

It was observed that five piles (20, 28, 32, 33 and 118) resulted in estimated values much higher than the values of the respective load tests, resulting in a high error and consequently changing the slope of the straight line down, considering that the projection of that line would be more adjusted to the slope of the pile grouping that is at the beginning of the line.

It was verified that all these piles mentioned above had the following characteristics in common: 1) N-values very high at the tip of the pile, generally not reaching the penetration of 30 cm of the split-spoon sampler and 2) the layers at the tip corresponded to sandy soils (specifically sands, silty sands and sandy silts). Through the equation of the line presented in the graph, it is also observed that for the estimated value it can approach the value of the load test, it should be multiplied by "0.6262", that is, the value should be reduced.

Again, the scatter plot was elaborated (Fig. 2), but now for the Aoki-Velloso results with the values of F1 and F2 automatically adopted by GEO5.

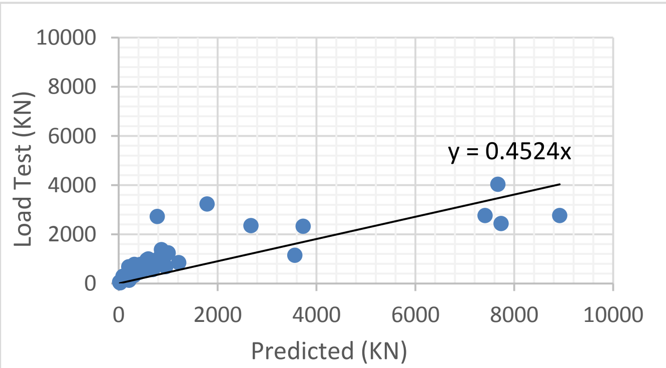

Figure 2. Scatter plot for F1 and F2 inserted automatically. Source: Authors.

It was observed that the same cuttings described above continued to stand out because their estimated values were excessively oversized. The graph also shows that the estimated values should be multiplied by a value lower than 1 (0.4524) in order to be able to approach the value of the load test.

A dispersion plot (Fig. 3) was constructed for the results obtained using the NavFac DM 7.2 method with Kdc=1.

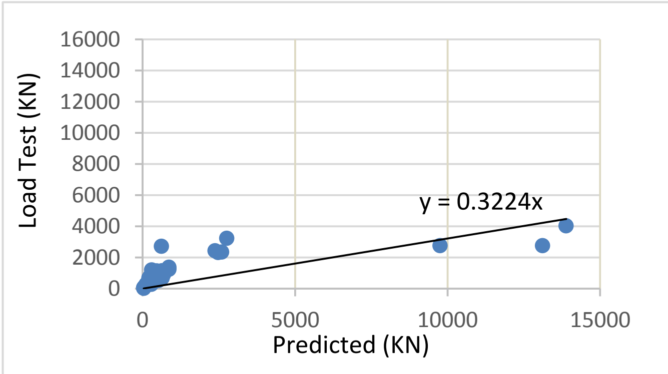

Figure 3. Scatter plot for NavFac DM 7.2 Method with Kdc=1. Source: Authors.

Once again it was observed that three piles (28, 32 and 33) resulted in ultimate bearing capacity values much higher than the corresponding load test values.

It was verified that all these piles mentioned above also had in common the same characteristics mentioned for the previous method. Through the equation of the line presented in the graph, it is also observed that the estimated values should be multiplied by "0.3224" in order to approximate the values of the load tests, that is, the estimated values should be reduced.

The scatter plot (Fig. 4) was also determined for the NavFac DM 7.2 methodology, but this time using Kdc=10 in sandy soils.

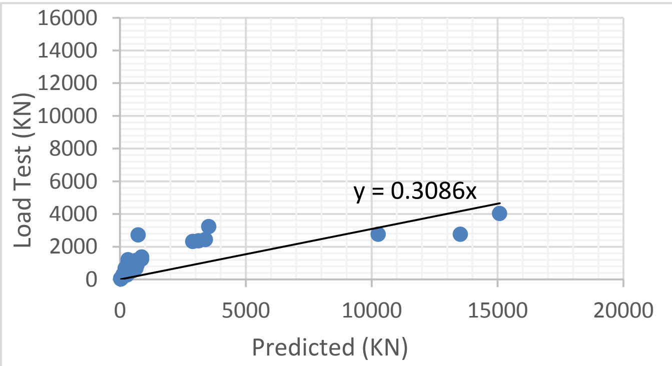

Figure 4. Scatter plot for NavFac DM 7.2 method with Kdc=10. Source: Authors.

Again, it was observed that the same three piles mentioned above continued to present exaggeratedly oversized values. The chart also shows that the estimated values should be multiplied by a value lower than 1 (0.3086) to approximate the values of the load tests.

B. *Adjusted results*

Soon after, adjustments were made in the results obtained by multiplying those values by the corresponding coefficient of the line found, obtaining the results presented in table 4.

TABLE IV. STATISTICAL RESULTS OBTAINED FOR EACH METHOD AFTER ADJUSTMENTS

	Aoki-Velloso		NavFac DM 7.2	
	F1and F2 manually added	F1 and F2 automatically added	Kdc=1	Kdc=10
Mean Percentage Error	53.75	60.39	75.24	74.35
Correlation	0.7999	0.7932	0.7601	0.7840
RMSE	705.76	730.25	872.28	849.23
Up to 10 % errors	1 of 48	0 of 48	0 of 48	0 of 48
Up to 20% errors	4 of 48	1 of 48	2 of 48	2 of 48
Conservative cases	43 of 48	45 of 48	45 of 48	45 of 48

It was observed that the mean percentage errors increased considerably in relation to the values obtained before adjustments were made. This was possibly due to the methods used to tend to provide (in general) conservative predictions. However, as has been previously reported, some piles had results with exaggerated overestimations, resulting in coefficients of adjustments lower than one, which when applied to group of piles tend to further reduce the estimated values and, therefore, further move them away from the reference values obtained in the load tests.

C. *Results excluding outliers piles*

Subsequently, the same procedure of accuracy verification was performed, but now without the piles that were considered outliers (20, 28, 32, 33 and 118) for presenting very high N-values at the tip of the pile (to the point of not reaching the penetration of 30 cm of split-spoon sampler) and presenting sandy soils at the base of the pile. In addition to the five piles mentioned above, two other piles (67 and 68) also presented the same characteristics and therefore were also considered outliers, totaling seven piles excluded in these new simulations. The results obtained are presented in table 5.

It was observed that in addition to the percentage error decreasing considerably in relation to when the load capacity was verified using all piles, it was also notorious that the NavFac DM 7.2 methodology significantly improved its load capacity forecast quality, bringing its margin of error closer to that of Aoki-Velloso. Regarding the correlation, the Aoki-Velloso method had a slight decrease, while NavFac dm 7.2 improved considerably.

Both methodologies obtained good results in relation to quadratic error, decreasing remarkably compared to the results obtained previously, mainly the methodology of NavFac DM 7.2 which managed to greatly reduce the error and approached to the values found with Aoki-Velloso method.

TABLE V. STATISTICAL RESULTS OBTAINED FOR EACH METHOD AFTER EXCLUDING OUTLIERS PILES

	Aoki-Velloso		NavFac DM 7.2	
	F1and F2 manually added	F1 and F2 automatically added	Kdc=1	Kdc=10
Mean Percentage Error	38.04	33.53	37,88	35.06
Correlation	0.7660	0.7799	0,8564	0.8558
RMSE	533.59	489.16	452,63	448.06
Up to 10 % errors	3 of 41	6 of 41	6 of 41	5 of 41
Up to 20% errors	10 of 41	16 of 41	10 of 41	10 of 41
Conservative cases	36 of 41	34 of 41	37 of 41	36 of 41

Regarding errors in the margin of 10% and 20%, the methodologies improved, not in absolute terms of the number of piles, but in the proportion of the results, that is, in terms of percentage in relation to the sample used.

After obtaining the above results without the outliers, the scatter plots were elaborated with the results of Aoki-Velloso with F1 and F2 inserted manually (Fig. 5) and with F1 and F2 added automatically (Fig. 6).

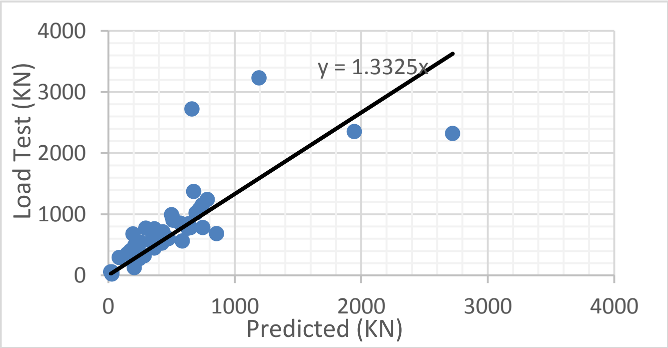

Figure 5. Scatter plot for F1 and F2 inserted manually after excluding outliers piles Source: Authors.

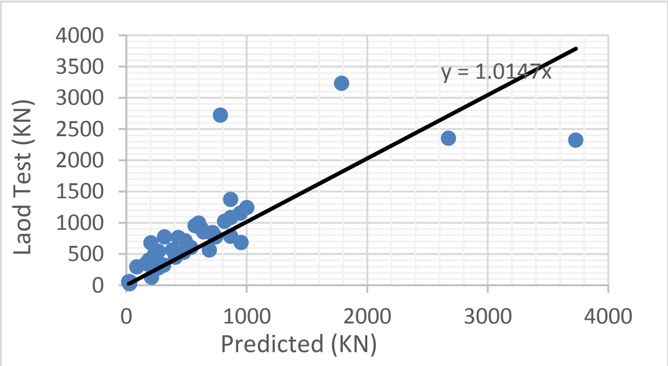

Figure 6. Scatter plot for F1 and F2 inserted automatically after excluding outliers piles. Source: Authors.

From those graphs, it was possible to verify that the coefficients of the lines became higher than 1 (1.3325 and 1.0147). It is believed that this occurred due to what has been mentioned earlier in relation to the Aoki-Velloso being a conservative method that tends to predict ultimate load capacities lower than load tests values.

Scatter plots (excluding outliers piles) were also elaborated with the results of NavFac DM 7.2 for Kdc =1 (Fig. 7) and Kdc =10 (Fig. 8).

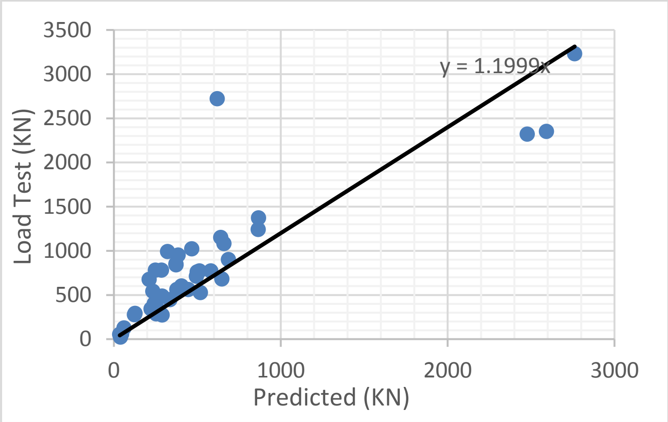

Figure 7. Scatter plot for NavFac DM 7.2 method with Kdc=1 after excluding outliers piles. Source: Authors.

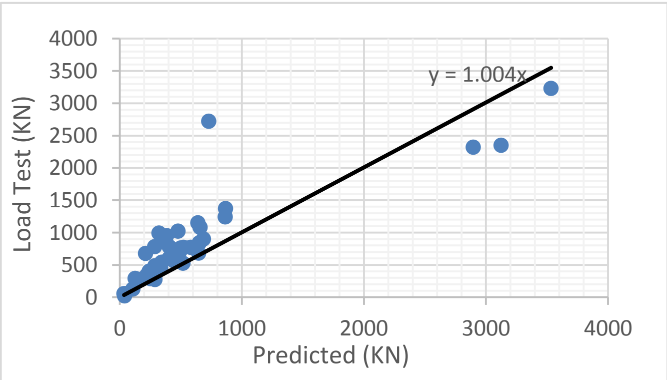

Figure 8. Scatter plot for NavFac DM 7.2 method with Kdc=10 after excluding outliers piles. Source: Authors.

D. Adjusted Results excluding outliers piles

Again, it was verified that the coefficients of the lines assumed a value higher and approximately equal to 1 (1.1999 and 1.004). Once again, it is believed that this occurred by NavFac DM 7.2 tending to predict lower load capacities than those obtained in load tests.

Again, the ultimate load capacities estimate for each pile were adjusted by multiplying them by the respective line coefficients, obtaining the results presented in table 6.

TABLE VI. STATISTICAL RESULTS OBTAINED FOR EACH METHOD AFTER EXCLUDING OUTLIERS AND AFTER ADJUSTMENTS

	Aoki-Velloso		NavFac DM 7.2	
	F1and F2 manually added	F1 and F2 automatically added	Kdc=1	Kdc=10
Mean Percentage Error	32.38	33.06	31.56	34.90
Correlation	0.7660	0.7799	0.8564	0.8558
RMSE	476.95	488.97	421.88	448.05
Up to 10 % errors	7 of 41	7 of 41	8 of 41	5 of 41
Up to 20% errors	17 of 41	16 of 41	17 of 41	10 of 41
Conservative cases	25 of 41	34 of 41	32 of 41	36 of 41

It is notorious the reduction of the average percentage error after the adjustment of the results without the outliers piles. It´s also remarkable the improvement of RMSE results, and the raise in the number of predictions within margins of 10% and 20% errors.

V. CONCLUSIONS

Of all that was analyzed, it was noticeable that at first the Aoki-Velloso method obtained the better ultimate load capacity predictions than the NavFac DM 7.2 method, as it was possible to observe in the results presented, which obtained the lowest error, the best correlation and the lowest root mean squared error. It was also verified that, for the two methods that were used, when the soil and the tip of the pile presents sandy characteristics and very high N-values, the predictions results seem to be compromised, since by excluding piles that presented such characteristics the results improved considerably.

It was observed that the NavFac DM 7.2 methodology was more favorable to safety than the Aoki-Velloso methodology, because in all comparations of results the NavFac method always returned a greater number of results lower than the load tests. However, it is also observed that the mean percentage error is still significant, because as presented in the results, in the first simulations the two methodologies presented errors close to 50% and later, after performing the adjustments, it was found that the average percentage errors were still around 30%.

Although the final results between the two methodologies are close, the Navfac method is considered more laborious because it was necessary to use a series of correlations to determine the values to be adopted for the parameters that were used, also resulting in considerable uncertainty. Since the results have come very close, they reinforce the idea of using the semiempirical method that uses the parameters available from SPT-type surveys.

From the present work, it’s noticeable the relevance of performing new comparative analyses between ultimate load capacities obtained for different methods such as Décourt-Quaresma and Aoki-Velloso, for other theoretical methods and the capacities obtained for other types of piles such as steel, Franki or bored piles.

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How to Cite this Article:

Silva, F. M. & Araujo, R. C. (2021). Comparison over the Accuracy of Ultimate Bearing Capacity Predictions of an Analytical and a Semiempirical Methods. International Journal of Science and Engineering Investigations (IJSEI), 10(116), 1-8. http://www.ijsei.com/papers/ijsei-1011621-01.pdf