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On the Use of the Concept of Match Quality of Settlements to Correlate Static and Dynamic Load Test in Franki piles

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ABSTRACT: This paper displays the usage of the concept of Match Quality of Settlement to correlate static and dynamic load tests in Franki piles. The High Strain Dynamic Pile Test (HSDPT) was operated according to the Dynamic Increasing Energy Test (DIET) proposed by Aoki (1989, 1997). The signal-matching analysis was implemented according to the new procedure through which the CAPWAP analysis may be performed in the DIET (Murakami, 2015). The initial studies observed that this procedure had shown positive correlations for precast concrete piles (Murakami, 2015). Murakami (2018) proposes using the littlest achievable shaft quake to access the best traditional match quality calculated on the Wave Up Curve. In this case, the HSDPT matches the Static Load Test's slope of the pile-top load versus the settlement curve at early loads. The dynamic test was carried out before the static test, and the CAPWAP analysis was done independently of the outcome of the static test. After the static test had performed, its results were compared with the dynamic test. The tests exhibited positive arrangement established on the graphical solution of the match quality of settlements (Murakami, 2018).

KEYWORDS: Dynamic load test, static load test, Franki piles, match quality of settlements, signal-matching, CAPWAP.

1 Introduction

The enterprise is placed in Barueri county, São Paulo, Brazil. A building was constructed in this location, and Franki Piles were designed to sustain the structure's loads. The deep foundations were driven from 16m to 19m depth, and the pile project diameter was 60cm. At the top of the deep foundation, a follower of the equivalent pile project diameter was connected to operate the dynamic load test. The borehole samples at this enterprise showed a soft silty clay through 8m depth, overlayed by a 12m-thick layer composed by a loose to very compact sandy silt. The ground water level was detected at 7m depth. The dynamic test (HSDPT) (pile E157) was positioned adjacent to the static load test (SLT) (pile E120), less than 7m distant. The impact loads were applied to the upper allocation of the pile by a 40kN drop hammer to collect the dynamic data.

2 Objectives

This paper aims to show the beneficial use of the concept of Match Quality of Settlement to correlate static and dynamic load tests in Franki piles. The Dynamic Increasing Energy Test (DIET), proposed by Aoki (1989, 1997), was used to implement the HSDPT. The CAPWAP analysis was done through the

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procedure proposed by Murakami (2015). It is displayed: a) the load vs. settlement curve of the SLT and HSDPT; b) force in the pile along the shaft for several impact loads analyzed through the signal-matching; c) damping force vs. pile-top velocity for several impact loads (first boundary condition); d) pile toe resistance vs. toe quake for each blow (second boundary condition); e) graphical solution of the match quality of settlements.

3 Background

The High Strain Dynamic Pile Testing – HSDPT (ASTM D4945, NBR 13208) intents to determine the pile capacity and the pile shaft integrity t. In the field, placed at highest level of the deep foundation, measurements are done from strain or force, and acceleration, velocity, or displacement transducers. Moreover, the HSDPT collects the force and velocity induced in a pile during a centric impact load. Engineering principles and judgment may be used by the Pile Testing Engineer to check out the captured data to inspect the impedance changes along the pile shaft, the efficiency of the hammer used to produce impact loads, and the peak tensile and compressive stresses appearing in a pile at the time of the event.

The transducers' signals shall be transferred at the moment of the impact load to the device for recording, processing, and displaying the data. The Pile Driving Analyzer (PDA) is a frequently used equipment to attain the dynamic data (Pile Dynamics, Inc, 2009).

Moreover, the dynamic data collected are analyzed through a signal-matching Method. The CAPWAP (Case Pile Wave Analysis Program) is a software commonly used to implement the signal-matching analysis (Pile Dynamics, Inc, 2006).

Good correlations between dynamic and static load test results have been observed since the 1980s by various authors: Likins and Makredes (1982), Fellenius et al. (1989), Niyama and Aoki (1991), Likins et al. (1996), Murakami (2015), Murakami et al. (2016), Murakami et al. (2018), Murakami et. Al. (2019). Traditionally, the SLT and HSDPT results are compared through the Davisson Offset Limit Load. When the deep foundation displacement is not enough to reach this limit load, Murakami (2015) proposed the Modified Davisson Limit Load.

Besides, Murakami (2015) proposed a new procedure through which the signal-matching analysis may be performed in the dynamic increasing energy test (DIET) (Aoki, 1989, 1997). It is established on the use of mathematical expression of the match quality of settlements and two boundary conditions. In this case, the CAPWAP analysis is performed for several impact loads with increasing energy following these considerations:

- The same shaft quake value and friction force along the shaft versus depth are used for all blows with increasing energy, except in blows with the lower energy that do not fully mobilize the shaft friction in the soil elements near the toe of the pile. In this case, the friction force reduces proportionally with the capacity, as predicted by the Smith soil model (Smith, 1960);
- The damping force is proportional to the pile-top velocity (first boundary condition), which is proportional to the applied energy at the top of the pile. For several impact loads, the signal-matching analysis is performed in order to maintain proportionality between the damping force and the velocity at the top of the pile;
- From the blow where the shaft friction is fully mobilized, any increase in capacity is due to additional pile toe resistance, which increases following the Smith's soil model until it is fully mobilized (second boundary condition). For each blow, a CAPWAP analysis is performed adjusting the relationship between the toe resistance and the toe quake value to be closer to the Smith's soil model;

When the pile capacity is fully mobilized in the HSDPT, the second boundary condition indicates a clear maximum value for the pile toe resistance, as shown in Figure 1 (Murakami, 2015).

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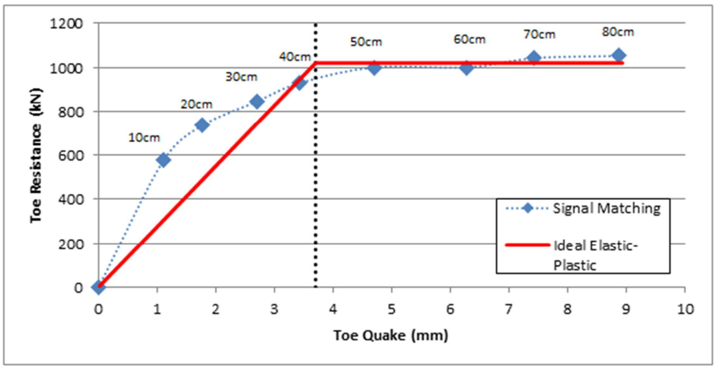

Figure 1. Maximum toe resistance in the second boundary condition (Murakami, 2015).

The initial studies on the use of this procedure showed good correlation among static and dynamic tests for precast concrete piles (Murakami, 2015; Murakami et al., 2016). Murakami (2018) proposed the use of the littlest achievable shaft quake to access the best traditional match quality, matching the slope of the pile top-load versus the settlement curve at the early loads. Besides, Murakami (2018) proposed a graphical solution of the match quality of settlements, plotting the settlement of the HSDPT and the SLT for each load increment of the SLT. The graph will show a number of points whose linear trend line passes through the origin (Eq. 1):

$$Y = \alpha \times X \qquad (1)$$

The closer the α and the coefficient of determination (R^2) are to the unity, the better will be the match quality of settlements.

4 Results

In the field, the HSDPT was done according to the DIET (Aoki, 1989, 1997). The drop hammer applied blows at the pile top with free fall among 40cm and 160cm, using height additions of 20cm. The HSDPT was done 70 days after the pile installation, and the SLT was executed 82 days after its installation. In the field, it was limited a blow with a free fall of 160 cm in order not to cause any damage to shaft. It was performed the signal-matching analysis in the blows with impact loads that caused a free fall of the hammer among 80cm and 160cm. In the seventh blow (160cm drop height) applied to the top of the pile, the results revealed that the impact load was sufficient to mobilize the shaft friction fully, demonstrating that the displacement of the pile was satisfactory in the soil elements near the toe of the pile to reach the qs value. In all the impact loads analyzed through the CAPWAP, the pile profile was the same, with small variations of the pile impedance along the shaft and a higher pile impedance near to the lower portion of the pile.

In the first to the sixth impact loads (free-fall between 40cm and 140cm), the signal-matching results demonstrated that the applied energy to the pile top was not plentiful to mobilize the friction force fully since the displacement of the pile near to the pile toe was not plentiful to achieve the shaft quake. In this case, a diminution of the qs value and the shaft friction in the lower portion of the pile was a necessity in order to obtain the best match, and it was proportional to the Smith's soil model.

In the analysis, the value for the shaft quake (qs) of 1.00 mm achieved the best Match Quality of the Wave Up curve (MQ_{WU}), likewise the best Match Quality of Settlements (MQ_S). In all the blows, the same qs value was used for all the elements of the soil on the shaft, except for the soil elements in the lower portion of the pile in the first to sixth blow (free-fall between 40cm and 140cm). Values of shaft quake higher than 1.00mm would increase both Match Qualities values (MQ_S and MQ_{WU}) for this pile.

A comparison between the SLT (Pile E120) and the simulated static load vs. settlement curve is shown in Figure 2. The HSDPT curve was obtained over the signal-matching analysis on the blow with a free fall of 160 cm (pile E157). A good match on the slope between the SLT and the signal-matching curve on the early

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loads is noted. The energy transmitted to the pile top was no plentiful to achieve the Davisson Offset on both tests. Then, the Modified Davisson Offset was used to compare the tests.

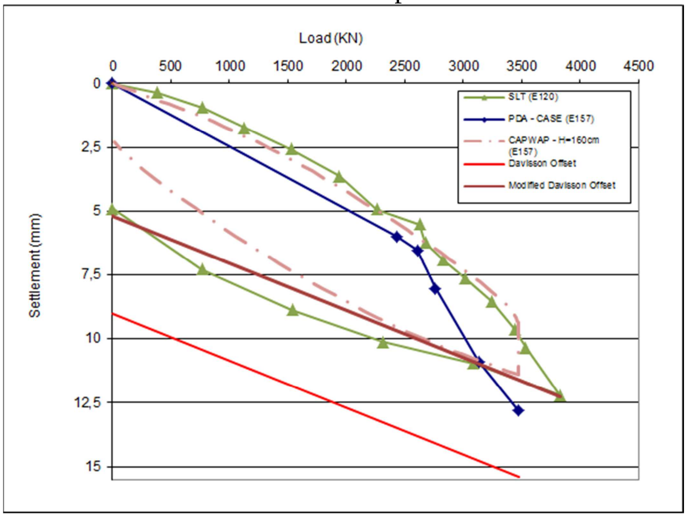

Figure 2. The results of the dynamic and static tests.

Distinct pile top-load vs. settlement curves are shown in Figure 3: a) Static Load Test (SLT) (pile E120); b) Static mobilized load (RMX) vs. maximum dynamic displacement (DMX) (pile E157); c) the signal-matching results for each blow (simulated static load vs. settlement curve) (pile E157); d) Davisson Offset limit load; e) Modified Davisson Offset limit load.

It is shown in Figure 3 that the Davisson Offset limit load is not reached in both tests. Then, a correlation between both tests was made through The Modified Davisson Offset limit load (Murakami, 2015), which indicated 3827 kN for the static test, while the dynamic test indicated 3470kN through the simulated static pile top-load vs. settlement curve (difference of -10.3%), and 3130 kN through the RMX vs. DMX curve (difference of -18,2%). The failure of the pile-soil interface was not observed through the shape of the RMX vs. DMX curve (Figure 2). Then, probably the difference among both tests would be reduced through the Modified Davisson Offset if a higher energy blow had occurred.

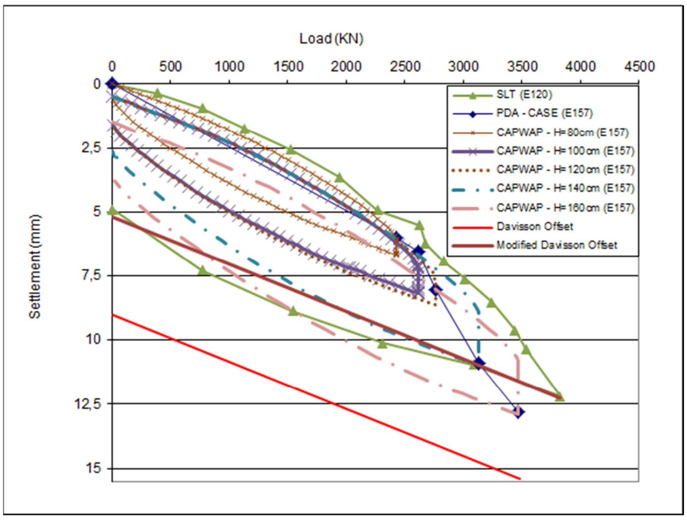

Figure 3. Results of dynamic and static test in the DIET.

For the impact loads analyzed using the signal-matching method, Figure 4 shows the pile force along the length curves (Pile E157). The first boundary condition is shown in Figure 5, plotting the damping force vs. the velocity at the top of the pile (Pile E157). It is noted a proportionality between the damping force and the velocity at the top of the pile.

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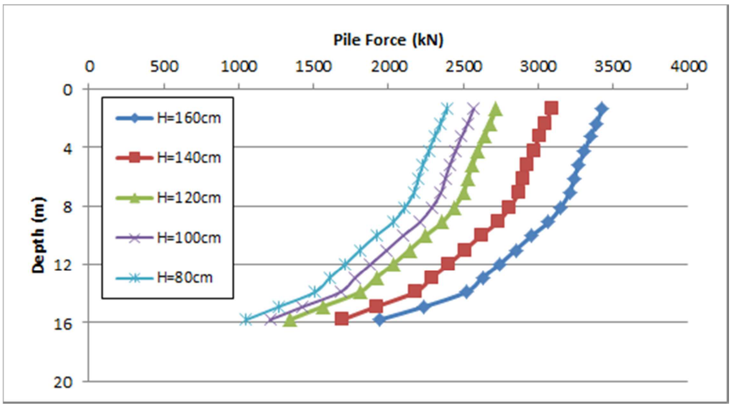

Figure 4. Force along the pile length (pile E157) (HSDPT).

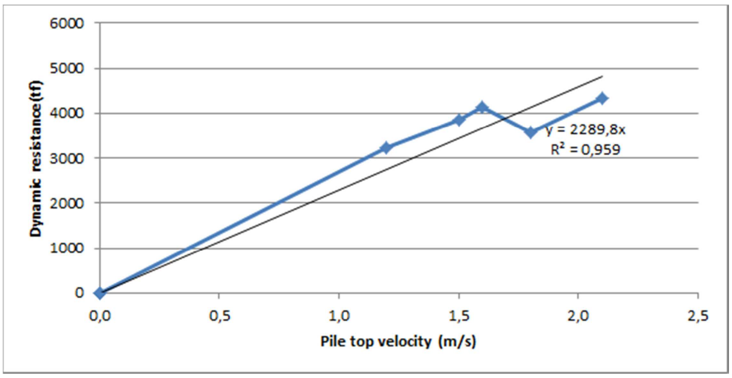

Figure 5. Damping force vs. velocity at the top of the pile (first boundary condition) (Pile 157).

Figure 6 illustrates the second boundary condition, in which it is plotted the resistance of the toe of the pile vs. the toe quake for each impact load analyzed using the signal-matching method(Pile E157). It is observed a linear pile toe response, and Figure 6 shows no evidence of maximum value for the resistance of the toe of the pile, as observed in Figure 1. It indicates that the pile capacity is probably higher than the result achieved in the maximum applied energy blow (160 cm). The measured set in this blow was 2 mm. The Davisson Offset limit loads (the Original and Modified) are strongly influenced by the shape of the pile top-load vs. settlement curve. Since it was not observed a maximum value for the resistance of the pile toe through the second boundary condition (Figure 6), the tests' difference would probably be reduced through the Modified Davisson Offset if a higher energy blow had occurred.

Table 1 shows that the analyzes reached good values of the MQ_S and MQ_{WU}. The value of the shaft quake higher than 1.00mm would deteriorate the MQ_{WU} and MQ_S, demonstrating that the likely shaft quake is the value used in the signal-matching analysis (1.00 mm) for this pile.

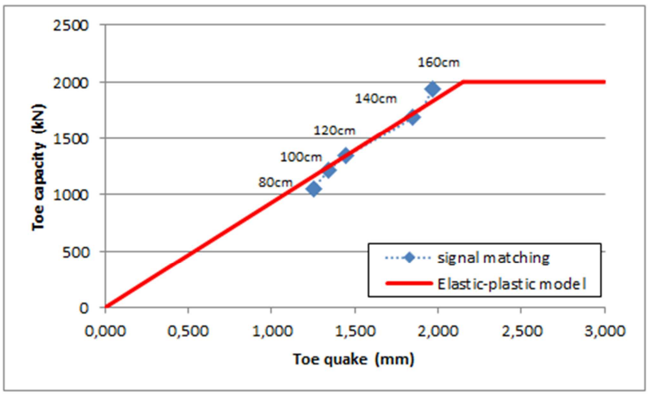

Figure 6. The resistance of the pile toe – signal-matching results vs. the Smith's soil model (Pile E157)

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Each impact load was analyzed by the signal-matching method and, the results of the graphical solution of the match quality of the settlements are shown in Figure 7. The MQ_S resulted in an R^2 among 0.985 and 0.990, and an α value among 1.001 and 1.186. The analyzes revealed MQ_{WU} values among 1.09 and 1.34.

Table 1 – Final Results for the pile E157

H (cm)	MQ_{WU}	α	R^2	RMX (kN)	Shaft Friction (kN)	Toe Resistance (kN)	Set (mm/blow)
80	1.10	1.118	0.988	2430	1380	1050	0.5
100	1.34	1.100	0.985	2610	1400	1210	1.0
120	1.39	1.095	0.990	2760	1420	1340	1.0
140	1.29	1.047	0.989	3130	1440	1690	2.0
160	1.09	1.001	0.985	3470	1530	1940	2.0

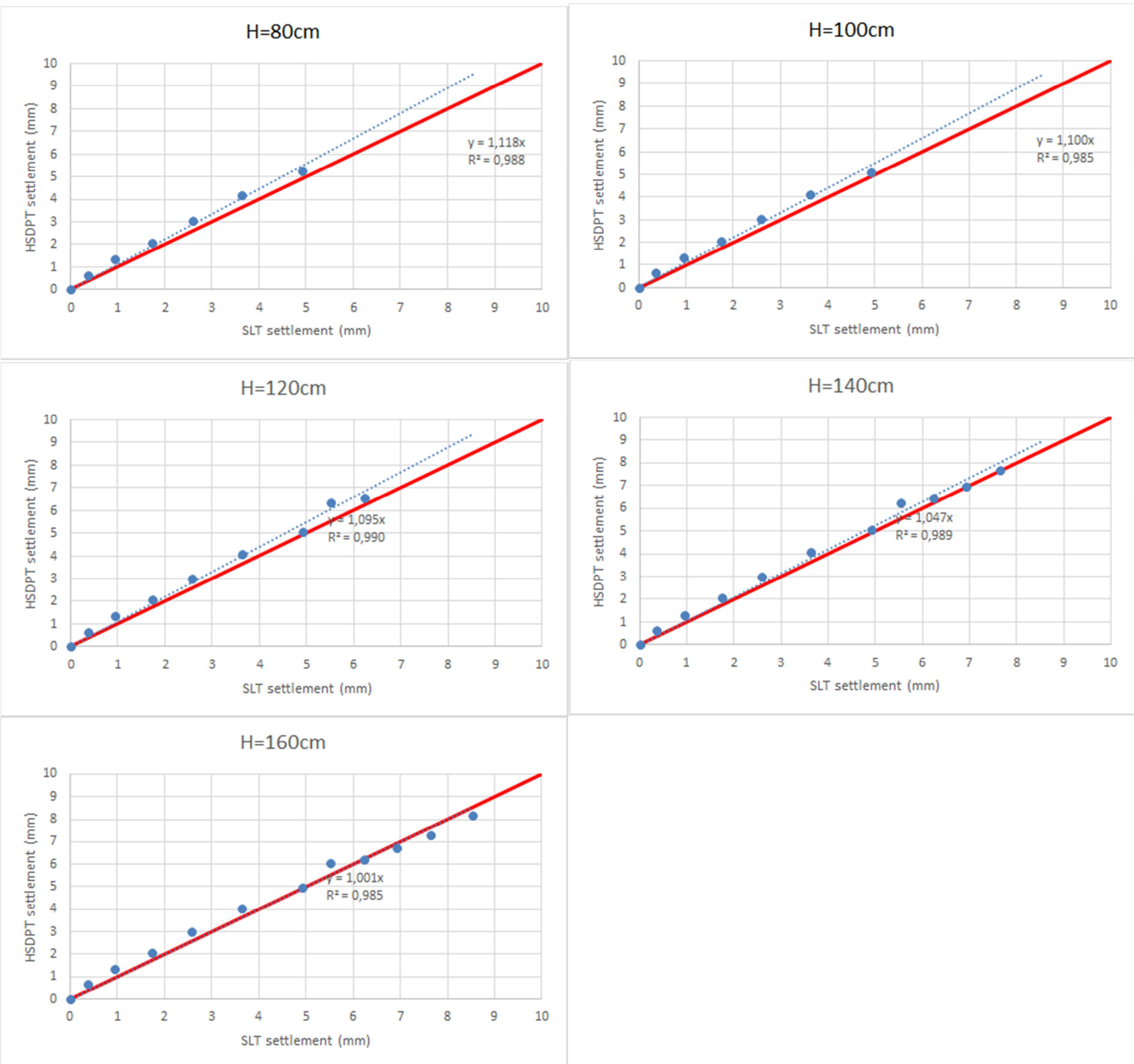

Figure 7. On the use of the Match quality of settlements in different blows (Pile E157)

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5 Conclusions

The Dynamic Load Test has been used intensively since the 1980s. It aims to determine the pile capacity and the pile shaft integrity. When it is made a comparison to the traditional Static Load Test, the HSDPT has some advantages, for example, the speed and the economy of the execution.

This paper aims to present an application of the use of the procedure proposed by Murakami (2015), through which the signal-matching method may be performed. This procedure intends to outcome better CAPWAP results, matching the slope of the simulated static mobilized pile top-load vs. settlement curve with the SLT's curve in the early loads through the Concept of The Match Quality of Settlements (Murakami, 2015, 2018). It contemplates minimizing the variation of outcomes or uncertainties associated with the application of the signal-matching method. The initial studies on the use of this procedure demonstrated positive agreement between dynamic and static tests for precast concrete piles (Murakami, 2015; Murakami et al., 2016). Nonetheless, it is shown in this paper that the procedure proposed by Murakami (2015) applies to Franki piles, as shown in this paper, steel pipe piles (Murakami et al., 2018), and CFA piles (Murakami et. Al., 2019).

The load determined through the Davisson Offset and the Modified Davisson Offset depends on the shape of the pile top-load vs. settlement curve. It was observed that the HSDPT resulted in a more conservative value on the load through the Modified Davisson Offset (-10.3% for the simulated signal-matching curve and -18.2% for the RMX vs. DMX curve). The difference in the load between both tests probably would be smaller if a blow with higher energy had been applied to the upper portion of the pile. In the field, it was limited a blow with a free fall of 160 cm in order not to cause any damage along the pile shaft. There are three reasons which indicate that the pile capacity of the pile tested by the HSDPT is higher than the one achieved in the CAPWAP analysis: a) It was not observed the failure of the pile-soil interface through the shape of the RMX vs. DMX curve (Figures 2 and 3); b) The full mobilization of the shaft friction occurred only in the last blow with a free fall of 160 cm; c) The second boundary condition (Figure 6) shows that the resistance of the pile toe is linear and no signs of the maximum value for the pile toe resistance was observed. However, the use of the concept of the Match Quality of Settlements demonstrated positive agreement among both tests, obtaining α and R^2 values close to the unity.

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