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The difference between physical and mathematical meaning in the dynamic load test

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Article

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Abstract

Dynamic Load Test (DLT) on piles has been used as an alternative to Static Load Test (SLT), offering cost savings and time reduction. Sensors at the pile top capture signals during the hammer impact. These signals are analyzed using the Signal-Matching Method to adjust calculated curves to measured data, varying parameters such as shaft friction and toe resistance. Different solutions may yield good Match Quality (MQ_{WU}). In CAPWAP, quality is traditionally assessed through MQ_{WU}, indicating the error between measured and calculated curves. Historically, DLT and SLT correlate well through the Davisson Method. However, Murakami (2015, 2019) observed discrepancies between simulated load vs. displacement curves of CAPWAP and SLT, introducing the Match Quality of Settlements (MQ_S) to enhance the Physical Meaning of the analysis. Improving MQ_S also enhances MQ_{WU}, achieved by the determination of the pile shaft quake along with two boundary conditions, constituting a New CAPWAP Procedure, resolving the variability of results uniquely. This paper explores the concepts of Physical and Mathematical Meaning in DLT and their impact on the execution and interpretation of CAPWAP.

1. Introduction

The Dynamic Load Test (DLT) or High-Strain Dynamic Pile Test (HSDPT) (ABNT 2007; ASTM, 2017) on piles has been extensively used as an alternative to the traditional Static Load Test (SLT), offering advantages in terms of cost and execution time. In the field, force and acceleration sensors are attached to the pile and collect signals from the hammer impact. Subsequently, the collected signals by the Pile Driving Analyzer (PDA) (Pile Dynamics, 2009) are analyzed using the Signal-Matching Method, where the best fit between measured and calculated curves is achieved through various attempts by varying soil parameters such as shaft friction distribution, toe resistance, quakes, and damping.

It is relatively easy to demonstrate that different solutions can yield satisfactory Match Quality values (Fellenius, 1988; Murakami, 2015; Verbeek, 2019). CAPWAP (Case Pile Wave Analysis Program) (Pile Dynamics, 2006) is the software typically used for the application of the Signal-Matching Method. Traditionally, the quality of CAPWAP analysis is evaluated by a number called Match Quality (MQ_{WU}), which represents the error between the measured and calculated Wave Up curve. The lower the MQ_{WU}, the better the Mathematical Meaning of the analysis, indicating a good approximation between the curves. Historically, several authors have concluded that DLT and SLT show good correlation through the Davisson Method, making a proper execution of the tests fundamental.

However, Murakami (2015, 2019) observed that despite the DLT showing good MQ_{WU} values and good correlation with the SLT through the Davisson Method, the Physical Meaning of the simulated CAPWAP curve could present discrepancies with the SLT curve when the load vs. settlement curves were superimposed. In this context, the concept of Match Quality of Settlements (MQ_S) emerged, initially through a Mathematical equation (Murakami, 2015) and later refined through a graphical solution (Murakami, 2019). The better the MQ_S, the more appropriate the Physical Meaning of the CAPWAP analysis should be. The author observed that optimizing the Physical Meaning also improved the Mathematical Meaning. This improvement was achieved by determining the pile shaft quake (Murakami & Massad, 2014, 2016), in conjunction with two boundary conditions, constituting a New Procedure for performing CAPWAP (Murakami, 2015, 2019), which uniquely solved the issue of variability in CAPWAP results.

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This paper aims to present the concepts of Physical and Mathematical Meaning (Murakami, 2015, 2024a) in the DLT and how this affects the execution and interpretation of the CAPWAP analysis. Compared to the previous publications (Murakami, 2015, 2024a), this paper intends to show a wide comprehension on how the Physical and Mathematical Meaning is affected by different conditions: a) pile types; b) experience of the person performing the dynamic test; c) quality of the collected data; d) Signal-Matching technique; e) the use of SLT results to improve the Signal-Matching Analysis; f) Limitations of the Signal-Matching Analysis without the SLT result.

2. Mathematical meaning

The quality of a traditional dynamic load test is evaluated through the concept of Match Quality, which essentially calculates the relative error between the measured and calculated curves in CAPWAP. The software allows for the verification of the Match Quality of three quantities: a) force, b) velocity, and c) Wave Up Curve.

The CAPWAP report typically displays the Match Quality of the Wave Up Curve (MQ_{WU}), which is given by Equation 1. This calculation is performed over four different periods, as indicated in Figure 1 (Pile Dynamics, 2006):

$$MQ = \sum_{Periods\ i-iv} \left(\sum_{time\ increments} \left| F_M - F_C \right| \right) / Fmax + MQ_B \tag{1}$$

where MQ is the Match Quality of the Wave Up Curve (MQ_{WU}), F_M is the Measured Wave Up Curve, F_C is the Calculated Wave Up Curve, F_{max} is the maximum value of the Wave Up Curve, and MQ_B is the penalty to the MQ when the difference between measured and calculated *set* is greater than 1 mm.

According to Pile Dynamics (2024), for good-quality collected signals, the MQ_{WU} should always be less than 5.0, usually less than 4.0, frequently less than 3.0, sometimes less than 2.0, and rarely less than 1.0. With experience, these numbers are more easily achieved, and the CAPWAP operator can, for example, obtain numbers below 2.0, except for concrete piles with damage or piles with very large sets, which are more challenging to analyze.

Klingmüller & Schallert (2019) highlight a hierarchy of complexity in DLT execution based on German experience. This complexity hierarchy also affects the difficulty of obtaining lower MQ_{WU} values. The authors note that the easiest piles to analyze are the first on the list below, while the most complex are at the end:

1. Uniform steel pile in compact sand;
2. Open-ended tubular steel pile with plugging in soils with different layers;
3. Steel or precast piles in soils with different layers;
4. Precast piles with damage;
5. Driven piles in clayey soils;
6. Cast-in-place piles in compact sand;
7. Cast-in-place piles in clayey soils;
8. Continuous flight auger piles, especially if they are displacement piles or cast-in-place piles with grout injection pressure.

Fellenius (1988), Murakami (2015, 2019), and Verbeek (2019) emphasize that the same collected signal can yield different outcomes in the CAPWAP analysis. This variation of outcome in the CAPWAP means that each of these analyses will have its own MQ_{WU}; in other words, the MQ_{WU} also depends on the experience of the person performing the analysis. Murakami (2015) and Likins et al. (1996) point out that CAPWAP has fully automatic (AT) tools to try to obtain the Best Match; however, these tools have not been able to surpass the quality of the analysis obtained by more experienced CAPWAP operators. It is worth noting that AT analyses are conservative, presenting lower mobilized loads (Murakami, 2015; Likins et al., 1996). Such automatic tools in CAPWAP should be used with caution and do not replace manual iterations by an experienced CAPWAP operator (Murakami, 2015, 2019).

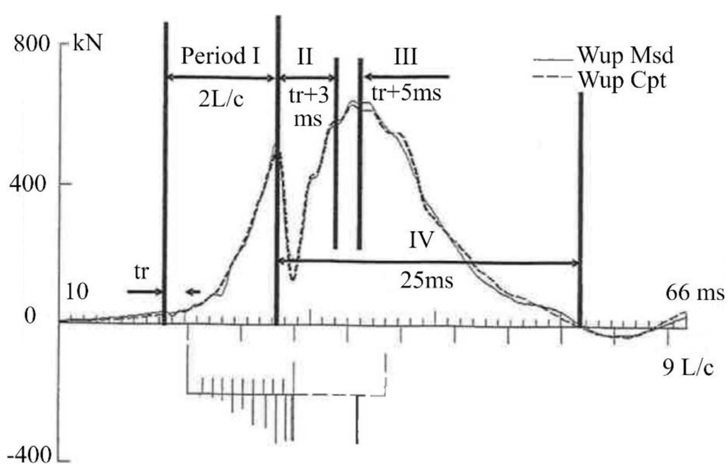

Figure 1. Indication of the four periods used in the calculation of MQ_{WU} (Pile Dynamics, 2006).

Furthermore, the CAPWAP manual (Pile Dynamics, 2006) highlights the importance of verifying the parameters used in the fully automatic analysis, such as the distribution of shaft friction and toe resistance, among others. As a practical Signal-Matching routine, even more experienced engineers use fully automatic (AT) tools or other specific automatic tools to reduce the time to perform the analysis. However, those tools may be used with caution, as observed by Murakami (2015).

A critical analysis of Equation 1 and the observations listed in this item allows us to observe:

- The calculation of MQ_{WU} is performed through the relative error between two quantities: a) measured, b) calculated.
- The calculated quantity is adjusted through various attempts to minimize the error in the measured quantity.
- If there are signal collection errors in the field (measured quantity), the Mathematical Meaning of Equation 1 may become invalid (see examples below).
- If poor signal quality is confirmed, even if the MQ_{WU} presents a satisfactory value, the quality of the CAPWAP analysis cannot be assured (see examples below).
- The value of the MQ_{WU} depends basically on two factors: a) the characteristic of the collected signal, where signals considered difficult may naturally present higher MQ_{WU} values; b) the experience of the person performing the analysis.
- Fully automatic (AT) CAPWAP analyses are conservative; however, they should be used with caution, mainly because they can present discrepancies from what is expected for the soil type, for example, in the distribution of shaft friction and toe resistance, among others.

Given the above, the MQ_{WU} indicates a Mathematical Meaning regarding the quality assessment of the CAPWAP analysis given by Equation 1, which may or may not have a Physical Meaning, as will be presented in item 3 of this article.

2.1 Analogy between CAPWAP and a professional artist

A high-level professional artist can replicate something in the form of a drawing based on an input, for example, a photograph of a person. If the artist is given a poor-quality photograph—for example, blurry, shaky, and with a dirty lens—this artist can faithfully replicate the photograph in the form of a drawing, including drawing it blurry, shaky, and indicating the dirt on the lens. In this case, the Match Quality of the drawing is excellent, as it managed to replicate what was in the photograph faithfully.

However, the photograph, due to its poor quality, does not faithfully represent reality and may even show no resemblance to the real person who was attempted to be replicated. In this case, the fault is not with the artist, who only replicated what was requested. Possibly, this artist could have done a better job if a higher-quality photograph had been presented. In that case, the drawing would have a better chance of resembling the real person one wishes to replicate in the form of a drawing.

In CAPWAP, the idea is the same. When there is a poor-quality signal, the result of the analysis may not faithfully represent the tested pile. In fact, trying to adjust the CAPWAP outcome (calculated quantity) with something of dubious quality (measured quantity), it may present discrepancies to the real behavior of the pile, such as mobilized load, compression, and tension stresses. Next, three case studies will be presented where the poor quality of the collected signal showed a completely different behavior of the pile, even with analyses indicating satisfactory MQ_{WU}.

2.2 Case study 1: São João de Meriti, RJ

This case study presents a root pile, therefore having a higher degree of complexity in the DLT execution according to Klingmüller & Schallert (2019). A deficiency in the collection of the force signal was observed. One of the sensors had a loose bolt, which resulted in strong oscillations in the measured force values. More information regarding this case study can be found in Murakami et al. (2022). Figure 2a shows the collected signal with poor quality, while Figure 2b shows the collected signal with good quality. In addition, both velocity signals are almost identical. Both CAPWAP analyses demonstrated satisfactory MQ_{WU} values; however, the analysis with a poor-quality signal indicated a lower mobilized load and also expressed false damage on the pile shaft.

The CAPWAP analysis of the collected signal from Figure 2a showed an impedance reduction of up to 55%, which would indicate severe damage to the pile (β = 45%). The mobilized load was 930 kN, and the MQ_{WU} was 3.63. In the CAPWAP analysis of Figure 2b, no signs of damage to the pile were indicated. The mobilized load was 1430 kN, and the MQ_{WU} was 1.36. It is noted that in the poor-quality signal (Figure 2a), the MQ_{WU} was satisfactory, which would commonly be accepted, and based on this CAPWAP analysis, the pile would be approved or not.

However, due to the poor quality of the collected signal, it did not indicate a good Physical Meaning, showing discrepancies in an analysis with a good quality signal (Figure 2b). The concept of Physical Meaning will be further explored. This case study clearly showed that the MQ_{WU} is not the only parameter to be analyzed, and it is fundamental to evaluate the quality of the collected signal, as proposed by Murakami (2024b).

2.3 Case study 2: Cubatão, SP

Murakami & Cabette (2024) show a case study on precast piles where the poor quality of the collected signal also indicated false damage to the pile. However, the cause

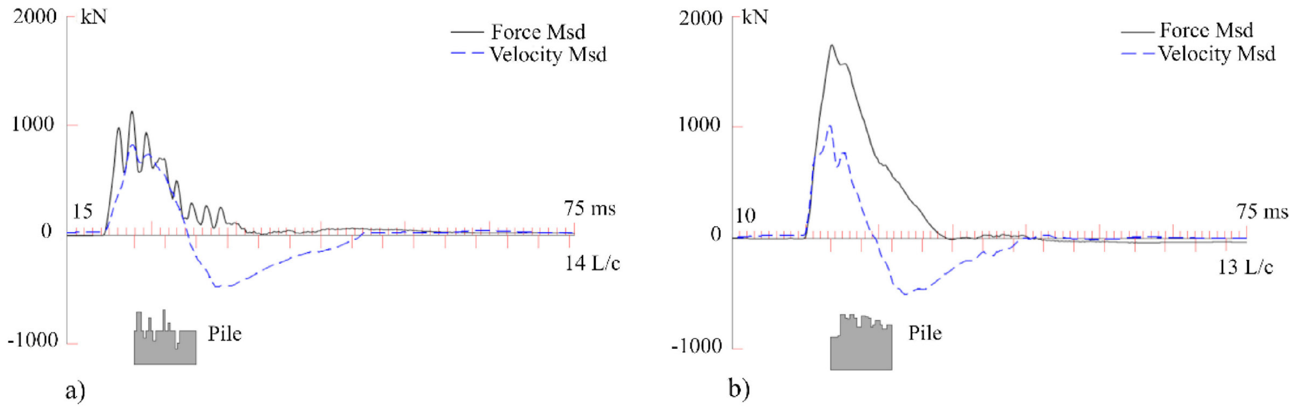

Figure 2. (a) Poor quality signal; (b) Good quality signal.

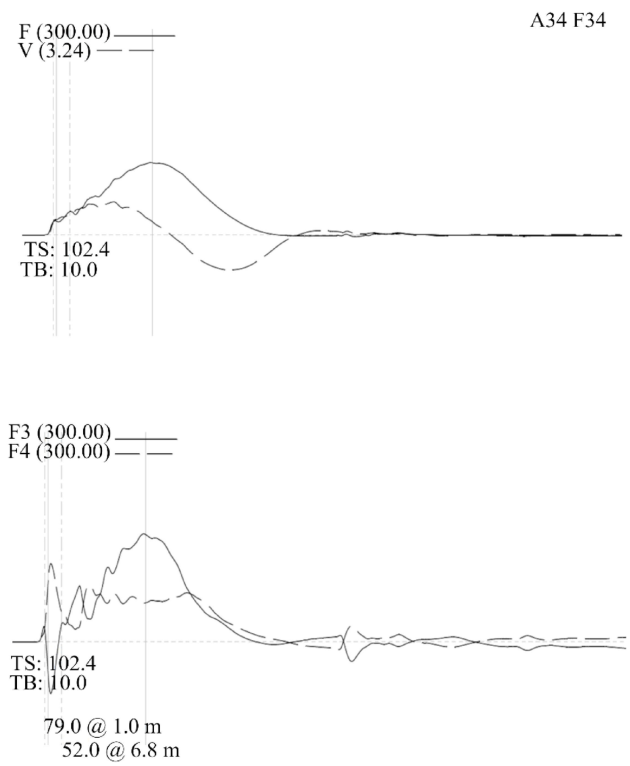

Figure 3. Bad quality data caused by an eccentric blow.

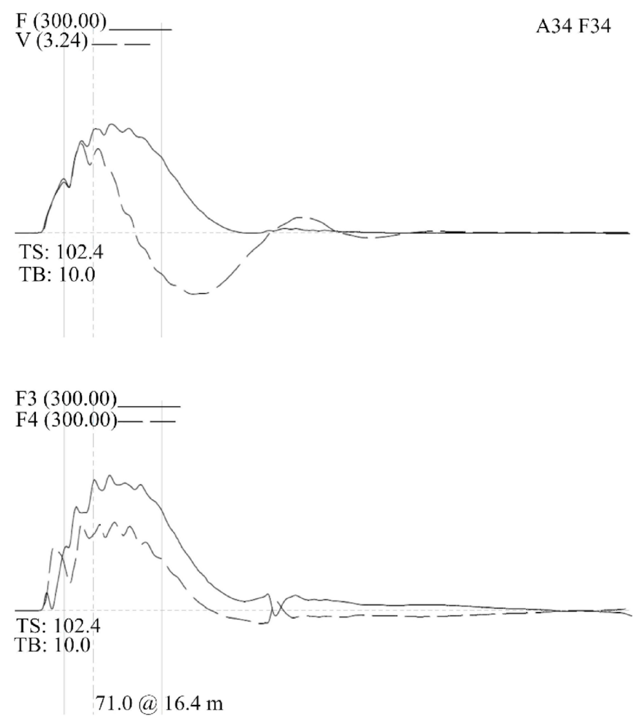

Figure 4. Good quality data after the adjustment of the pile driving machine.

of the poor signal quality was an eccentric blow on the pile that caused negative force values before the 2L/c period in one of the pair of sensors (sensor F3), indicating that this bending on the pile may have resulted in this “false pile damage.” Figure 3 shows the bad-quality collected data. In addition, it is noted a β value of 52%. In this case, because the β is less than 60%, this pile could be considered broken.

Further, the pile-driving machine’s hammer had been appropriately adjusted (Figure 4) with no indication of negative values at the beginning of the strike on sensor F3. Moreover, the β values were 71% and the CAPWAP demonstrated slight damage on the pile, with two compression slacks (0.10mm with an efficiency of 0.10 at 12.11m and 0.25mm with an efficiency of 0.20 at 17.15m) and one tension slack (10 kN with an efficiency of 1.0 at 1.0 m).

This case study shows that the pile testing engineer may evaluate if the collected data demonstrates good quality. If not, an investigation must be done to identify the cause of the bad-quality data. Otherwise, the results of the HSDPT will not be reliable and may indicate false pile damage on the pile shaft.

2.4 Case study 3: Guarujá, SP

This is an unusual case study on precast concrete piles (Murakami & Cabette, 2023), as normally, the wave equation theory shows that increasing the cushion thickness should reduce compression and tension stresses. However, in this case, the effect was the opposite. The discrepancy in behavior from what was expected is due to the poor quality of the collected signal. Placing a thicker cushion on top of the pile caused a poor signal collection, indicating a false negative force signal, as shown in Figure 5a, while Figure 5b shows the good quality signal on the same pile, both with the same drop height of 40cm.

Table 1 shows the comparison of the results between the poor and good quality signals. In this case, these parameters of the poor-quality signal were obtained by the Case Method through the *JC* (Case Damping Factor) obtained from the analysis of the good quality signal. It is noted that all the parameters indicated in Table 1 were totally divergent. Although no CAPWAP analysis was performed on the poor-quality signal, this case study clearly showed a discrepancy in the results. A possible CAPWAP analysis on the poor-quality signal, even with an acceptable MQ_{WU} value, would not present a good Physical Meaning. This concept of Physical Meaning will be further explored.

3. Physical meaning

Murakami (2015) proposed the concept of Match Quality of Settlements (MQ_S) through an equation similar to the MQ_{WU}. This equation allows the evaluation of the quality of the simulated CAPWAP curve when an SLT is available for comparison.

$$MQ_S = \sum_{0}^{n} \left(\left| Y_{ci} - Y_{cwi} \right| + \left| Y_{ci+1} - Y_{cwi+1} \right| \right) \times \left(P_{i+1} - P_i \right) / \left(2 \times Y_{cmax} \right) \quad (2)$$

where Y_{ci} is the settlement from the static load test, Y_{cwi} is the settlement from CAPWAP, P_i is the load associated with settlement Y, n is the number of points from the load test, and Y_{cmax} is the maximum settlement from the static load test; MQ_S = Match Quality of Settlements.

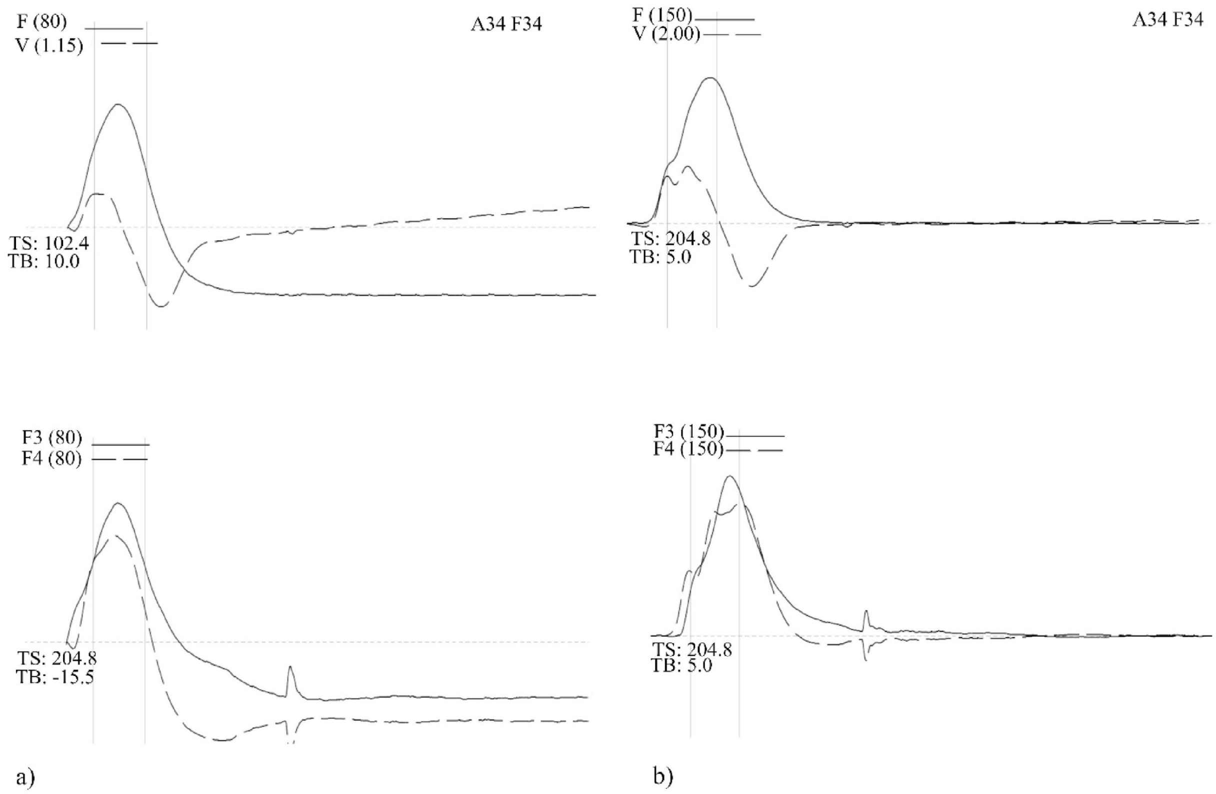

Figure 5. (a) Poor quality signal; (b) good quality signal.

Table 1. Comparison of results from poor and good quality signals.

Signal	*RMX* (tons)	*CSX* (MPa)	*CSI* (MPa)	*Set* (mm/ blow)	*EMX* (tons.m)	*DMX* (mm)	*TSX* (MPa)	*FMX* (tons)
Bad quality	44	5.4	6.1	0	0.09	2	3.1	48
Good quality	103	11.6	13.0	0	0.55	8	0.8	103

Legend: RMX = mobilized static resistance; *CSX* = average compression stress; *CSI* = maximum compression stress; *Set* = permanent deformation in the blow; *EMX* = energy applied to the pile; *DMX* = maximum dynamic displacement; *TSX* = maximum tension stress; *FMX* = maximum force measured by the sensors.

Subsequently, Murakami (2019) further developed this concept through a graphical solution by plotting the SLT settlement on the X-axis and the simulated CAPWAP curve settlement on the Y-axis for each stage of the SLT, forming a series of points whose linear regression may be represented by Equation 3:

$$Y = \alpha \times X \quad (3)$$

Murakami & Massad (2023) highlight the advantages of using the MQ_S concept: a) it allows the comparison of the CAPWAP with the SLT regardless of the need for a minimum toe displacement; b) it allows for the comparison of all points of the SLT and not just a pair of points as given by the Davisson Method or the Modified Davisson Method by Murakami (2015); c) the traditional procedure for comparing the SLT and CAPWAP does not provide information regarding the pile settlement at the design load.

It is also worth noting that, despite the simplicity of the graphical solution of MQ_S (Murakami, 2019) compared to the Mathematical equation (Murakami, 2015), the new version provides additional information: it is possible to verify if the CAPWAP settlements are greater or smaller than the SLT settlements by evaluating the value of α.

When the values of α and R^2 of the MQ_S are close to unity, it indicates that the simulated CAPWAP curve is very close to the SLT curve, showing good Physical Meaning. On the other hand, when the value of α is less than one, it indicates that, on average, the SLT settlements were greater than the CAPWAP settlements. In contrast, values of α greater than one would indicate that the CAPWAP settlements were greater than those of the SLT. In several case studies, it was observed that the improvement of the MQ_{WU} was obtained when there was also an improvement of the MQ_S; that is, an improvement of the Mathematical Meaning measured by the MQ_{WU} was accompanied by a refinement of the Physical Meaning measured by the MQ_S, as will be shown next.

3.1 The influence of the shaft quake on the MQ_S

Fellenius (1988) observed that the CAPWAP results might vary as a function of the operator who performs the analysis, depending on the soil type. In general, Fellenius (1988) concluded that the total static mobilized capacity varies little for different operators. Qualitatively, there was agreement on the shaft-friction distribution when analyzed by different operators. However, the damping and quake values might be different.

During the 10th Stress Wave Conference, Verbeek (2019) noted that there is a growing awareness around the world that the bearing capacity determined through the Signal-Matching Method is highly dependent on the assumptions made by the person performing the analysis, leading to a wide range of results.

Verbeek & Bielefeld (2022) states that the greatest difficulty of the Signal-Matching Method is that there is no unique solution, as the system with multiple soil layers having different resistance, quake, and damping parameters is too complex to allow for a closed-form solution. The final result of the analysis depends on the interpretation of the CAPWAP operator. It is not necessarily a definitive bearing capacity, but rather the best assessment of the operator who performed the analysis regarding the pile's capacity, which is clearly something subjective.

In the same Conference that Verbeek (2019) noted the variations of the results of the Signal-Matching Method, Murakami (2019) proposed a Signal-Matching technique to improve the DLT results. Initially, a Signal-Matching analysis is performed to obtain the best match and the static pile capacity. Then, the shaft quake is adjusted to match the initial slope of the pile-top load vs settlement curve of the SLT or, less reliably, by the SLHW (Static Loading with the Hammer Weight of the Pile Driving Machine). The other variables are adjusted to obtain the new Best Match of the Wave-Up curve.

The new solution obtained by this procedure, correcting the shaft quake (*qs*), might result in a pile capacity close to the traditional procedure, and also matches the slope of the SLT's curve. In addition, an improvement may be observed in both match qualities, Wave-Up curve (MQ_{WU}), and the Match Quality of Settlements (MQ_S).

Table 2 shows the Signal-Matching parameters that should be adjusted to obtain the new best MQ_{WU}, divided into two periods. Period 1 is the first 2L/c time, and period 2 is the after 2L/c time. For example, in period 1, if the *qs* value increases, then the RS or *SS* should increase to improve the MQ_{WU}. If the *qs* value decreases, then the RS or *SS* should decrease to improve the MQ_{WU}.

Figure 6 shows the influence of the *qs* values on the MQ_S in a case history. The solution named DK shows the analysis performed by the technique proposed by Murakami (2019). In this case history, it is observed that a reduction in the *qs* values improved the α and R^2 values of the graphical solution of the MQ_S.

Table 2. Signal-Matching parameters that should be adjusted to improve the MQ_{WU} (Murakami, 2019).

Period	*qs*	Increase	Decrease
1	increase	*RS*, *SS*	-
1	decrease	-	*RS*, *SS*
2	increase	*SS*, *ST*, *UN*	*CS*, *QT*, *CT*
2	decrease	*CS*, *QT*, *CT*	*SS*, *ST*, *UN*

Where: RS (Static Shaft Friction); *SS* (Smith Shaft Damping); *ST* (Smith Toe Damping); *QT* (Toe Quake); *UN* (Unloading Level); *CS* (Shaft Quake Multiplier); *CT* (Toe Quake Multiplier).

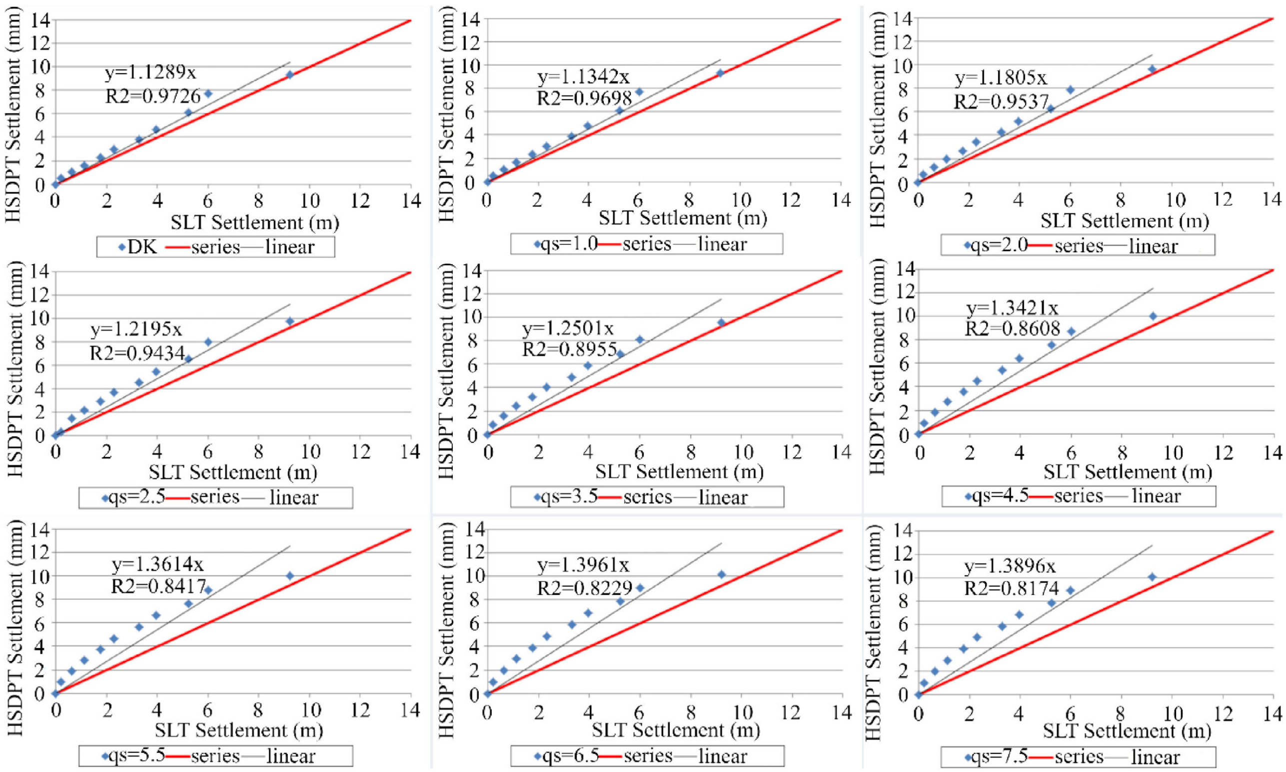

Figure 6. Influence of the *qs* on the MQ_S (Murakami, 2019).

3.2 The influence of the shaft quake on the load vs. settlement curve

Murakami (2019) showed the influence of the *qs* values on the shape of the load vs. settlement curve. Figure 7 illustrates it. The chart on the left of Figure 7 is an enlargement of the initial slope of the chart on the right. Note that the slope at the beginning of the curve is directly proportional to the shaft quake. In addition, all the CAPWAP analyses shown in Figure 7 have almost the same pile capacity, with good MQ_{WU}. However, the shape of the load vs. settlement of the CAPWAP is different.

Moreover, the improvement of the simulated load vs. settlement of the CAPWAP is associated with the improvement of the MQ_S and MQ_{WU}. In other words, the improvement of Physical Meaning measured by the MQ_S is followed by the improvement of the Mathematical Meaning measured by the MQ_{WU}.

3.3 Various case studies

Table 3 indicates several case studies by Murakami where the MQ_S concept allowed for the improvement of the MQ_{WU}; that is, an improvement of the Physical Meaning (MQ_S) was accompanied by the refinement of the Mathematical Meaning (MQ_{WU}).

It is observed that initially, the MQ_S concept was successfully applied to precast concrete piles (Murakami & Massad, 2014, 2016; Murakami, 2015; Murakami et al., 2016). However, it was found that this concept also applies to other types of piles, such as steel, CFA, and Franki piles (Murakami et al., 2018, 2019, 2020, 2025a, b; Souza et al., 2025).

3.4 Limitations of the signal-matching analysis without the SLT result

When the SLT result is not available, Murakami (2019) observed that the best MQ_{WU} is reached through the use of the smallest *qs* value possible to obtain the best MQ_S. When there is no information regarding the pile load-movement relationship through the SLT or SLHW, Murakami (2019) recommends the use of the lowest *qs* value possible in order to obtain the best MQ_{WU}.

A case study presented by Murakami et al. (2020) uses this procedure. The dynamic load test was performed prior to the static load test, and the corresponding CAPWAP analysis was conducted independently of the SLT results. Subsequently, the results from both tests were compared. This comparison revealed a positive correlation based on the graphical solution of the Match Quality of Settlements (MQ_S) with α value of 1.001 and R^2 of 0.985 for the drop height of 1.60 m (Figure 8). The MQ_{WU} was 1.09, indicating an excellent match. In addition, the best MQ_{WU} and MQ_S were obtained through the use of the *qs* value of 1.00 mm.

Table 3. Different case studies were analyzed by Murakami.

Case Study	Pile type	Diameter (m)	Pile length (m)	Load		α	R^2	Authors
				DLT (kN)	*SLT* (kN)			
Osasco, SP	Precast	0.38	13.80	1990	1905	1.13	0.97	Murakami & Massad (2014, 2016)
Jacarei, SP	Precast	0.20	15.35	825	835	1.20	0.96	Murakami (2015)
Rio Claro, SP	Precast	0.50	16.15	3025	2650	0.98	0.99	Murakami et al. (2016)
Itapoá, SC	Steel pipe	1.00	40.00	7880	7290	0.97	0.99	Murakami et al. (2018)
Atibaia, SP	CFA	0.30	16.00	1255	1280	1.46	0.99	Murakami et al. (2019)
Barueri, SP	Franki	0.60	18.00	3470	3827	1.00	0.99	Murakami et al. (2020)
Rio de Janeiro, RJ	Steel	W310x32.9	15.50	520	486	0.810	0.98	Murakami et al. (2025a)
Bertioga, SP	CFA	0.30	15.00	590	500	1.14	0.96	Murakami et al. (2025b)
Santos, SP	Steel	HP310x79.0	43.30	2880	2700	0.85	0.99	Souza et al. (2025)

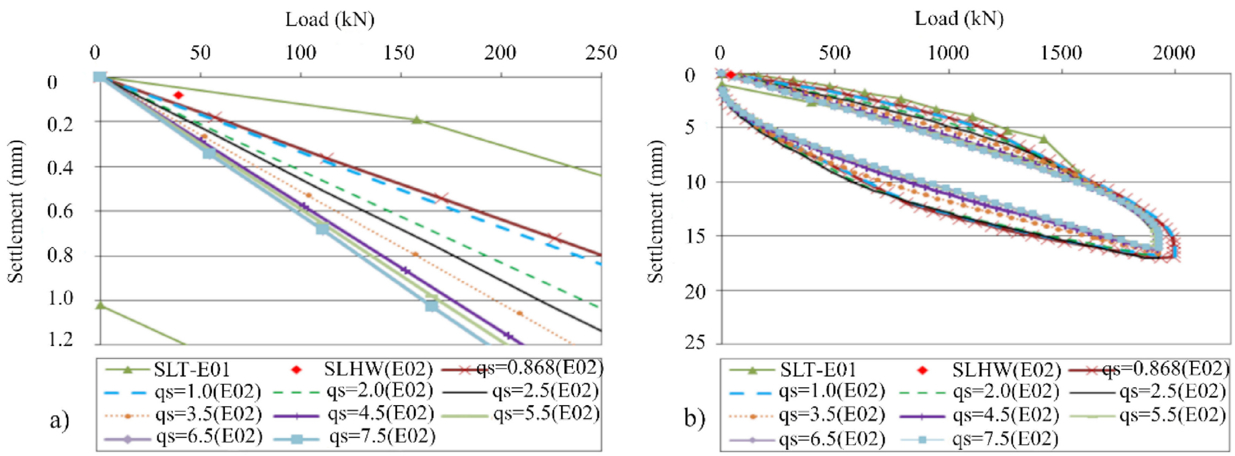

Figure 7. The influence of the shaft quake on the load vs. settlement curve (Murakami, 2019). (a) first stages of the SLT; (b) all stages of the SLT.

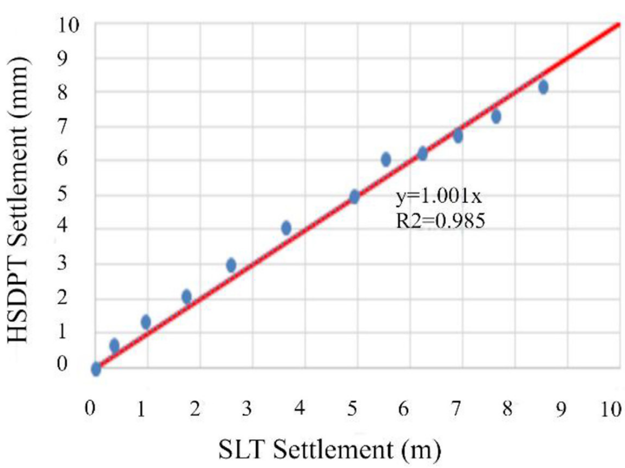

Figure 8. Match Quality of Settlements (MQ_S) applied to a Franki pile.

4. Final considerations

Murakami (2015, 2024a) introduced the concepts of Mathematical Meaning and Physical Meaning in the dynamic load test. Initially, the Mathematical Meaning of the CAPWAP analysis was measured by the Match Quality of the Wave Up Curve (MQ_{WU}). In contrast, the Physical Meaning was measured by the Match Quality of Settlements (MQ_S).

Compared to the previous publications (Murakami, 2015, 2024a), this paper intended to show a wide comprehension on how the Physical and Mathematical Meaning is affected by different conditions: a) pile types; b) experience of the person performing the dynamic test; c) quality of the collected data; d) Signal-Matching technique; e) the use of SLT results to improve the Signal-Matching Analysis; f) limitations of the Signal-Matching Analysis without the SLT result.

In this paper, these concepts were further explored, providing a more detailed explanation of the meaning of the traditional Match Quality (MQ_{WU}) calculation. It was shown that the MQ_{WU} strongly depends on the quality of the collected signal, as Equation 1 clearly shows that the calculated quantity must equal the measured quantity for the MQ_{WU} value to be as low as possible. When there are signal collection errors, the MQ_{WU} value may not have a Physical Meaning. It may even show discrepancies compared to a well-collected signal, as shown in the case studies presented in this article.

It was also shown that the MQ_{WU} value depends basically on two factors: a) the complexity hierarchy of the DLT execution (Klingmüller & Schallert, 2019); b) the experience of the person performing the CAPWAP analysis (Fellenius, 1988; Murakami, 2015, 2019; Verbeek, 2019; Pile Dynamics, 2024).

There is a similarity between CAPWAP and a high-level professional artist. Both can replicate the input data; however, if this input data is of poor quality, the final result may be different from what is expected. In the case of CAPWAP, the mobilized load and stresses in the pile material may be different when compared with a good-quality signal. In the case of the artist, the drawing of the person who was attempted to be replicated may not show resemblance to the real person.

The MQ_S concept initially arose through an equation (Murakami, 2015) and was later improved through a graphical solution (Murakami, 2019). It is also worth noting that, despite the simplicity of the graphical solution of MQ_S (Murakami, 2019) compared to the Mathematical Equation (Murakami, 2015), the graphical solution provides additional information (Murakami & Massad, 2023): it is possible to verify if the CAPWAP settlements are greater or smaller than the SLT settlements by evaluating the value of α.

When the values of α and R^2 of the MQ_S are close to unity, it indicates that the simulated CAPWAP curve is very close to the SLT curve, showing good Physical Meaning. On the other hand, when the value of α is less than 1, it indicates that, on average, the SLT settlements were greater than the CAPWAP settlements. In contrast, the values of α greater than one would indicate that the CAPWAP settlements were greater than those of the SLT.

In several case studies, it was observed that the improvement of the MQ_{WU} was obtained when there was also an improvement of the MQ_S; that is, an improvement of the Mathematical Meaning measured by the MQ_{WU} was accompanied by a refinement of the Physical Meaning measured by the MQ_S.

Declaration of interest

The author has no conflicts of interest to declare.

Data availability

The datasets generated and analyzed in the course of the current study are available from the corresponding author upon reasonable request.

Declaration of use of generative artificial intelligence

This work was prepared with the assistance of generative artificial intelligence (GenAI) Grammarly Pro with the aim of evaluating grammar checking in English. The entire process of using this tool was supervised, reviewed, and when necessary, edited by the author. The author assumes full responsibility for the content of the publication that involved the aid of GenAI.

List of symbols and abbreviations

n	number of points from the load test
qs	shaft quake of the pile
set	permanent deformation in the blow
AT	fully automatic CAPWAP
CAPWAP	Case Pile Wave Analysis Program
CS	Shaft Quake Multiplier
CSI	maximum compression stress
CSX	average compression stress
CT	Toe Quake Multiplier
DK CAPWAP	analysis performed by the technique proposed by Murakami (2019)
DLT	Dynamic Load Test
DMX	maximum dynamic displacement
EMX	energy applied to the pile
F_C	Calculated Wave Up Curve
F_M	Measured Wave Up Curve
FMX	maximum force measured by the sensors
HSDPT	High-Strain Dynamic Pile Test
JC	Case Damping Factor
MQ_B	penalty to the *MQ* when the difference between measured and calculated *set* is greater than 1 mm
MQ or MQ_{WU}	Match Quality of Wave Up Curve or Traditional Match Quality
MQ_S	Match Quality of Settlements
P_i	load associated with settlement Y
QT	Toe Quake of the pile
RS	Static Shaft Friction
R^2	coefficient of determination
SLHW	Static Loading with the Hammer Weight of the Pile Driving Machine
SLT	Static Load Test
SS	Smith Shaft Damping
ST	Smith Toe Damping
TSX	maximum tension stress
UN	Unloading Level
Y_{ci}	settlement from the static load test
Y_{cmax}	maximum settlement from the static load test
Y_{cwi}	settlement from CAPWAP
α	angular coefficient of the MQ_S
β	parameter to evaluate the pile integrity

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