The Advantage of The Use of The Concept of Match Quality of Settlements in The Dynamic Load Test

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ABSTRACT: Murakami and Massad (2014, 2016) proposed a method to determine the shaft quake values in the Dynamic Load Test (DLT). Based on the concept of Match Quality of Settlements (MQ_S), the signal-matching analysis was performed to adjust the slope of the load vs. settlement curve at the early loads of the Static Load Test (SLT). Initially, the MQ_S concept was a mathematical expression that measured the difference between the SLT and DLT's load vs. settlement curves. This procedure provided good results for precast concrete piles. However, in the following years, it was observed that the MQ_S concept also applies to other pile types. Furthermore, Murakami (2019) improved the MQ_S concept through a graphical solution, plotting the settlements of the SLT vs. DLT for each load increment of the SLT. Traditionally, the SLT and DLT results are compared by the Davisson Offset Limit, requiring a minimal toe displacement. Besides, it displays two points on the load vs. settlement curves, one for the SLT load and the other for the DLT load. This paper aims to present the advantage of the MQ_S concept: all the points of the SLT curve are compared with the DLT curve, not requiring a minimal toe displacement.

KEYWORDS: Match Quality of Settlements (MQ_S), Static Load Test (SLT), Dynamic Load Test (DLT), CAPWAP, Davisson Offset Limit, Pile Settlements

RESUMO: Murakami e Massad (2014, 2016) propuseram um método para determinar os valores do quake do fuste no Ensaio de Carregamento Dinâmico (ECD). Com base no conceito de Match Quality de Recalques (MQ_R), o método signal-matching foi realizado para ajustar a inclinação do trecho inicial da curva de carga x recalque da Prova de Carga Estática (PCE). Inicialmente, o conceito de MQ_R era uma expressão matemática que media o erro entre as curvas de carga x recalque da PCE e ECD. Esse procedimento proporcionou bons resultados para estacas pré-moldadas de concreto. Porém, nos anos seguintes, observou-se que o conceito de MQ_R também se aplica a outros tipos de estacas. Além disso, Murakami (2019) aprimorou o conceito de MQ_R por meio de uma solução gráfica, plotando os recalques da PCE vs. ECD para cada incremento de carga da PCE. Tradicionalmente, os resultados da PCE e ECD são comparados pelo Método de Davisson, exigindo um deslocamento mínimo da ponta da estaca. Além disso, esse método mostra dois pontos nas curvas carga x recalque, um para a carga da PCE e outro para a carga do ECD. Este trabalho tem como objetivo apresentar a vantagem do conceito de MQ_R: todos os pontos da curva da PCE são comparados com a curva do ECD, não exigindo um deslocamento mínimo da ponta da estaca.

PALAVRAS CHAVE: Match Quality de Recalques (MQ_R), Prova de Carga Estática (PCE), Ensaio de Carregamento Dinâmico (ECD), CAPWAP, Método de Davisson, Recalque de Estacas

1 Introduction

The High Strain Dynamic Pile Testing (HSDPT) or the Dynamic Load Test (DLT) (ASTM D4945, NBR 13208) has been performed intensively worldwide due to the speed and economy of its execution. Since the 1980s, many authors have shown good correlations of the DLT with the static loading test (SLT) (ASTM D4945-12, NBR 16903), and the results are traditionally compared through the Davisson Offset (1972), which requires a minimal toe displacement, as shown in Equation 1. The intersection of Equation 1 with the load vs. settlement curve is the offset-limit load defined by Davisson (Figure 1).

$$Ru = \frac{P \times L}{E \times A} + \frac{D}{120} + 4 \quad (1)$$

Where: Ru = Ultimate load; L = Pile length; E = Elastic modulus; A = cross sectional area; D = pile diameter in millimeter;

However, in some cases, the maximum settlement of the pile is not sufficient to reach the Davisson Offset in the DLT or the SLT. In this case, Murakami (2015) proposed the Modified Davisson Offset (Figure 1), which is a parallel line to that of the original method, passing through the lowest settlement between the maximum values of the DLT and SLT curves.

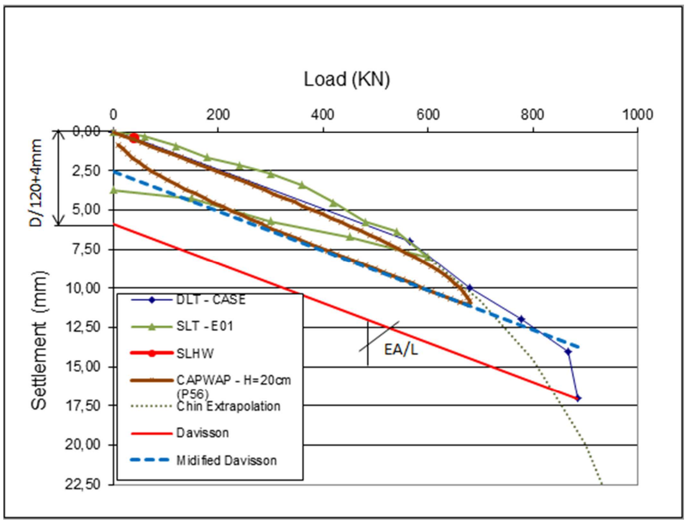

Figure 1. Modified Davisson Offset (Murakami, 2015)

According to Rausche et al. (1994), the collected data obtained in the field may be further analyzed by the CAPWAP (Case Pile Wave Analysis Program) (Pile Dynamics, Inc., 2006) to evaluate the shaft friction in-depth, the toe capacity, the soil model parameters (damping and quakes values). Further, it may predict the load vs. movement relationship at the pile top. CAPWAP is a signal-matching method, and its results are based on the "best possible match" between a computed top variable, such as the pile top force, and its measured equivalent. It is, therefore, a calculation made by several attempts. It is not a closed solution.

In some specific cases, the solution inevitably obtained by the CAPWAP results in high toe quake values, as observed by some authors, for example, Authier and Fellenius (1980), Likins (1983), Murakami and Cabette (2014 and 2022). In these cases, the non-use of high toe quake values causes the match quality number to increase considerably, deteriorating the quality of the CAPWAP.

However, according to Fellenius (1988), the CAPWAP might show variations of results as a function of the operator, who executes the analysis, as well as on the soil type. In general, this author concluded that the static mobilized load varies little when analyzed by different operators, being able to present more significant variation in more peculiar soils. However, the damping and quake values might be different. In fact, according to Murakami (2015), the shaft friction distribution in depth might differ from that expected due to the soil type depending on the shaft quake value used in the CAPWAP analysis.

The DLT has some advantages and some uncertainties in its application (Svinkin, 2004). The CAPWAP analysis, as a signal-matching procedure, has no answer regarding the existence and uniqueness of the best approximation of a measured curve. Feedback from the match quality number is evidence of some uncertainty in determining the pile capacity by signal matching. A comparison of static and dynamic test results is a complicated problem because the results of the DLT depend on several factors, such as the time between the tests, the time after pile installation, the set-up rate, the sequence of tests, the pile type, the blow counts, the type of signal-matching technique, the quality of the dynamic records, and the soil conditions.

In order to try to solve the variation of the CAPWAP results as a function of the operator and present a solution that is closer to the reality in the physical aspects (and not only in the mathematical solution measured by the match quality), Murakami (2015 and 2019) proposed a new procedure to perform the CAPWAP analysis through the determination of the shaft quake value (qs). It uses the new concept of match quality of settlements (MQ_S) for signal matching analysis to determine the qs values. This new concept needs a pile top load vs. settlement of the Static Load Test (SLT) in a pile tested through the DLT.

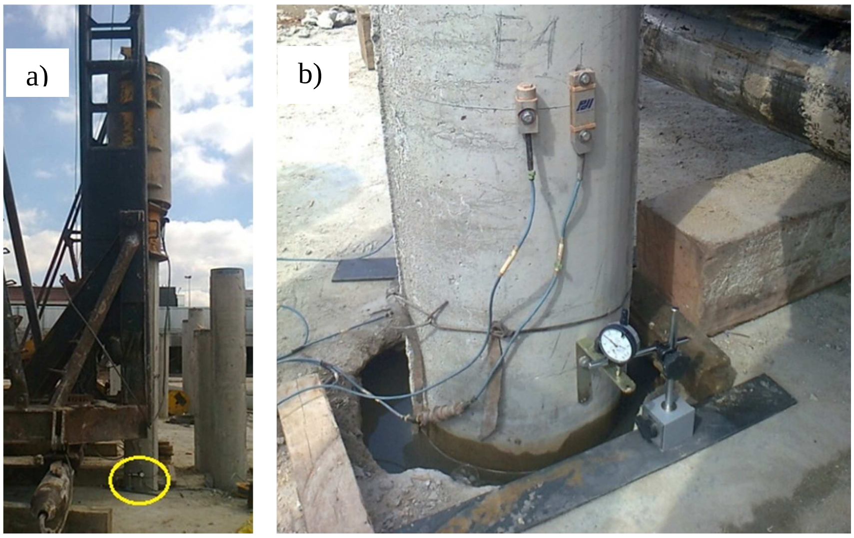

Fig 2 – (a) Performing a static loading using the hammer’s weight of the pile driving machine (SLHW) (b) Reading the pile top settlement with displacement indicators

When the top load vs. settlement of the SLT is not available, Murakami (2015 and 2019) proposed a static loading test with the hammer's weight of the pile driving machine (SLHW) before performing the dynamic testing, measuring the pile top settlement using displacement indicators according to ASTM D1143 and NBR 16903.

This procedure has the advantage of not requiring the installation of the reaction piles, reducing cost and time of execution, as well as representing the pile behavior at the exact moment of the dynamic test (the set-up effect is neglected). Figures 2a and 2b show the procedure for performing the SLHW.

2 Match Quality of Settlements (MQ_S)

Initially, the CAPWAP is done according to the traditional procedure, which means reaching the best match and determining the static pile capacity. Then, the shaft quake value is adjusted to match the initial load-settlement curve of the SLHW or, somewhat, of the SLT (Murakami and Massad, 2014 and 2016). The other variables are also adjusted, reaching the new best match of the wave up curve.

The match quality of settlements (Murakami, 2015) is defined by the equation (2):

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

Where: Yci = settlement of the static load test (SLT); Ycwi = settlement of the CAPWAP; Pi = corresponding load of the settlement Y; n = number of load increments of the static load test; Ycmax = maximum settlement reached on the static load test; MQ_S = match quality of settlements.

Murakami (2019) improved the MQ_S concept with a graphical solution which correlates the settlement of the static loading test with the settlement predicted by the CAPWAP for each load increment of the SLT. The chart shows a series of points whose trend line is given by an expression passing through the origin (3):

$$y = \alpha \times x \tag{3}$$

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

3 Case Studies

Table 1 shows different case studies where the concept of MQ_S was used to correlate the DLT and SLT. Initially, the MQ_S concept was applied to precast concrete piles. However, in recent years, it was observed that this concept also applies to other pile types, for example, steel piles, CFA piles, and Franki piles.

The DLTs shown in Table 1 were performed according to the Dynamic Increasing Energy Test (DIET), proposed by Aoki (1989 and 1997), and the CAPWAP analyses were performed according to the procedure proposed by Murakami (2015, 2019).

Table 1 –Case Studies that used the concept of MQ_S to correlate the DLT and SLT

Case Studies	Pile Type	Diameter (m)	Length (m)	Load Capacity DLT (kN)	Load Capacity SLT (kN)	α	R^2	Authors
Osasco, SP	Round Precast	0.38	13.80	1,990	1,905	1.13	0.97	Murakami et al (2014, 2016)
Jacarei, SP	Square Precast	0.20	15.35	825	835	1.20	0.96	Murakami (2015)
Rio Claro, SP	Round Precast	0.50	16.15	3,025	2,650	0.98	0.99	Murakami et al (2016)
Itapoá, SC	Steel Pipe	1.00	40.00	7,880	7,290	0.97	0.99	Murakami et al (2018)
Atibaia, SP	CFA	0.30	16.00	1,255	1,280	1.46	0.99	Murakami et al (2019)
Barueri, SP	Franki	0.60	18.00	3,470	3,827	1.00	0.990	Murakami et al (2020)

For the first case history (Osasco-SP), Figure 3 shows the influence of the qs values on the α and R^2 values. For this case study, the solution named DK reached the best MQ_S (lowest α and R^2 values closest to 1) and the best MQ_{WU}.

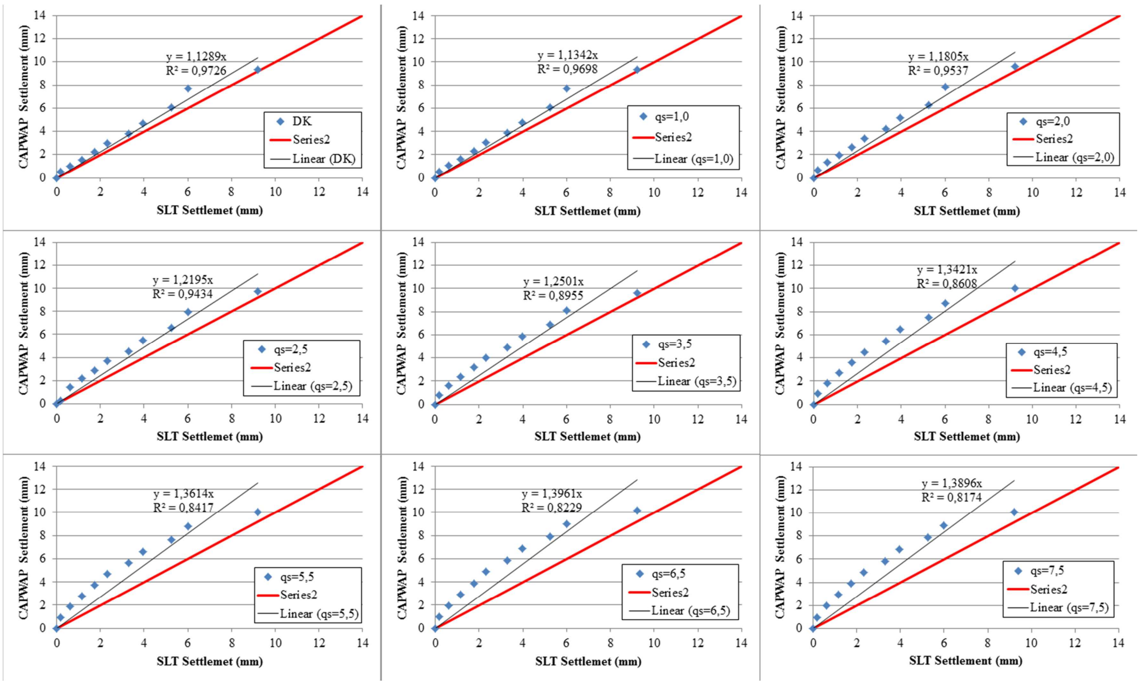

Figure 3 – The influence of the qs value on the Graphical solution of the MQ_S

The other cases, analyzed similarly, revealed values of α and R^2 close to the unit, indicating a good correlation between the DLT and SLT.

4 Prediction of pile settlements for the Osasco Case Study

For the Osasco case study, Figure 4 shows the influence of the qs value on the load vs. settlement curves of the CAPWAP. It may be seen that the pile settlements at the maximum load are close for different qs values. However, at the design load of 790kN, the predicted settlements are different depending on the qs values.

Figure 5 shows an enlargement of the initial slope of the graph shown in Figure 4. Note that the slope at the beginning of the curve is directly proportional to the shaft quake. Moreover, the CAPWAP analysis with the shaft quake value of 0.868 mm provided: a match between the signal-matching settlement (0.12 mm), the SLHW movement at 39 kN (0.08 mm), and the SLT curve of Pile E01 (0.05 mm at 39 kN).

Figure 6 allows the comparison of the best MQs (qs=0.868mm) and the worst MQs (qs=6.5mm) curves. The analysis shows that the best MQ_S curve is closer to the SLT curve (difference of 29.0% on the pile settlement at the design load), while the difference associated with the worst MQs is 111.2%. Furthermore, the MQ_S concept considerably improved the load vs. settlement curve, representing the closest possible match with the SLT curve.

Svinkin (2004) commented that comparing static and dynamic test results is a complex problem due to several factors. Although the pile capacity may be close for analyses with different qs values, the shape of the load vs. settlement curves is quite different. Even with the best MQ_S and MQ_{WU} analyses, there is not a "perfect" match on the pile settlements (MQ_S) (difference of 29.0% at the design load). One explanation would be that the DLT was performed six days after the pile installation, while the SLT was performed 72 days after the pile installation. Usually, an older pile tested by the dynamic or static test will show a stiffer response on the load vs. settlement curve.

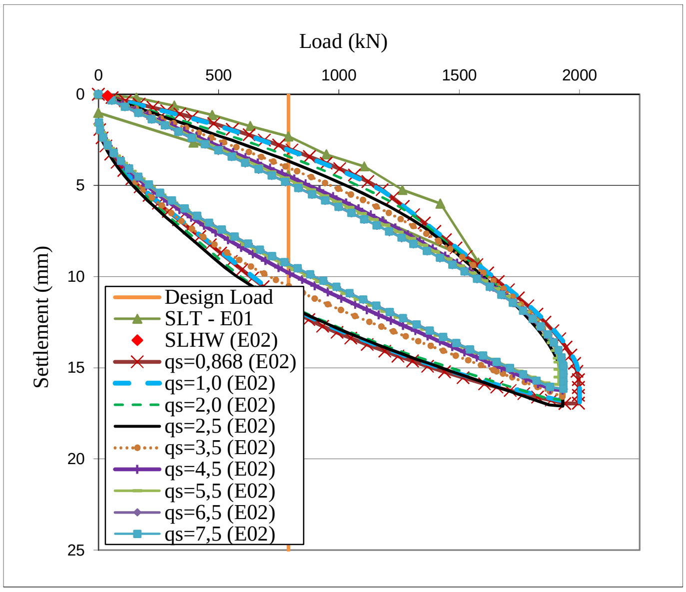

Figure 4 – The influence of the qs value on the prediction of the pile settlements

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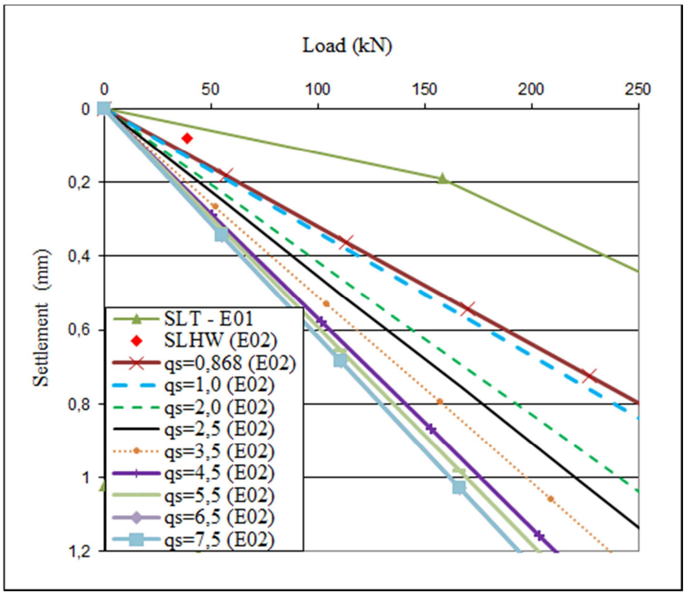

Figure 5 – The influence of the qs value on the prediction of the pile settlements at the early loads

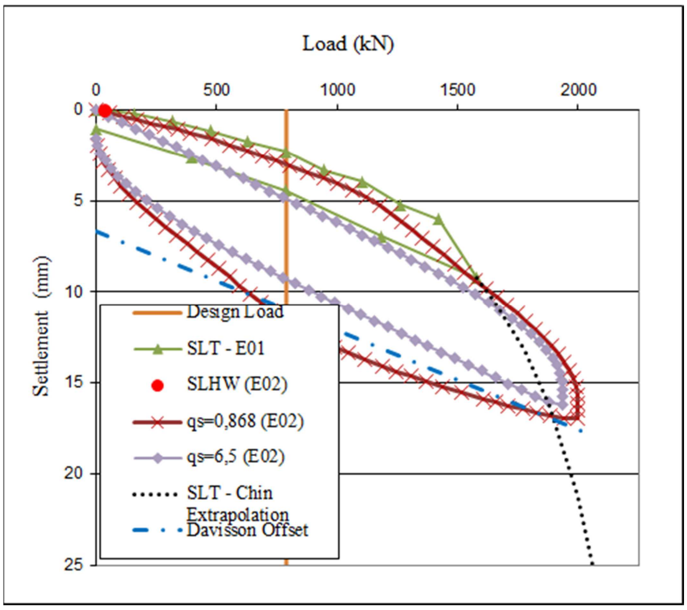

Figure 6 – A comparison between the best MQs (qs=0.868mm) and the worst MQs (qs=6.5mm) on the pile settlements

For different qs values, Table 2 shows the results of: a) the CAPWAP settlements Y_{CW} at the design load (790kN); b) MQ_{WU}; c) MQs (α and R^2), and d) RMX (Maximum Static Resistance). The Y_{CW} and the RMX values were compared, respectively, with 2.31mm, the pile settlement of the SLT at the design load, and 1,905 kN, the maximum load of the SLT, as indicated in Figure 6 (Davisson Offset). For the Osasco case study, the difference in Y_{CW} increased with qs, the same occurring with MQ_{WU} and α. The values of R^2 varied in reverse, moving away from the unit. Moreover, the improvement in the MQ_{WU} values indicates that using the Match Quality of Settlements (MQ_S) may provide the best prediction of the load vs. settlement curve. In addition, the MQ_S concept has the advantage of comparing all the points of the SLT and the DLT load vs. settlement curves. On the other hand, the traditional procedure uses only a pair of points (Davisson Offset) to correlate both tests, not providing any information regarding the pile settlement at the design load.

Once the number of the piles tested through the DLT is usually higher than the SLT, later, the analysis performed through the MQ_S concept may be helpful for soil-structure analysis in which the settlement of the piles is predicted to verify the rearrangement of the load on the piles. Furthermore, the parameters obtained by the signal-matching may be used to predict the load vs. settlement curves of the other piles that were not tested by the DLT or SLT.

Table 2 – Comparison of settlements at the design load (Y_{CW}), MQ_{WU}, MQ_S, and RMX for different CAPWAP analysis

Analysis	Y_{CW} (mm)	Difference in Y_{CW} (mm)	(%)	MQ_{WU}	α	R^2	RMX (kN)	RMX Difference (kN)	(%)
Qs = 0.868	2.98	0.67	29.0	1.34	1.1289	0.9726	1,996	91	4.8
Qs = 1.000	3.06	0.75	32.4	1.50	1.1342	0.9698	1,996	91	4.8
Qs = 2.000	3.41	1.10	47.6	1.64	1.1805	0.9537	1,930	25	1.3
Qs = 2.500	3.66	1.35	58.4	1.83	1.2195	0.9434	1,930	25	1.3
Qs = 3.500	4.03	1.72	74.5	1.87	1.2501	0.8955	1,930	25	1.3
Qs = 4.500	4.50	2.19	94.8	1.89	1.3421	0.8608	1,930	25	1.3
Qs = 5.500	4.67	2.36	102.1	1.93	1.3614	0.8417	1,913	8	0.4
Qs = 6.500	4.88	2.57	111.2	2.05	1.3961	0.8229	1,933	28	1.5
Qs = 7.500	4.89	2.57	111.3	2.01	1.3896	0.8174	1,842	-63	3.3

5 Conclusions

The paper showed how to determine the value of the pile's shaft quake (qs) using the MQs concept, which involves comparing the SLT and DLT load-settlement curves. For this purpose, a mathematical expression and a graphical solution was successfully applied to 5 case studies, involving precast concrete, steel, CFA and Franki piles. It was shown that the lower the value of the MQ_S of the mathematical expression and the closer to the unit are the α and the R^2 values of the graphical solution, the better the CAPWAP results are.

In one case study, the static loading test with the hammer's weight of the pile driving machine (SLHW) was used, reducing time and cost of execution, presenting the advantage of not being influenced by set-up effects. It gave the initial slope of the pile top load vs. settlement curve, which is strongly influenced by the shaft quake value, as predicted by the Smith model.

It was also shown that the MQ_S concept has the advantage of comparing all the points of the SLT and the DLT load vs. settlement curve, not requiring a minimal toe displacement. A CAPWAP analysis with the best MQ_S may also provide the best match with the load vs. settlement of the SLT, which provides the best prediction of the pile settlement at the design load as well as the best correlation with the SLT at the maximum load.

In contrast, the traditional procedure to compare SLT with DLT uses a pair of points from Davisson Offset to correlate both tests and requires a minimal toe displacement. Once some SLT or DLT may not reach a minimal toe displacement, this is a disadvantage of the traditional procedure. In addition, the traditional procedure to compare both tests may not provide any information regarding the pile settlement at the design load.

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