Comparison of CPT averaging methods for estimating the pile base resistance

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ABSTRACT

During press-in pile penetration and loading, the resistance underneath the pile base is affected by an influence zone a certain distance above and below the pile tip. To estimate the strength of this influence zone, design methods often use the Cone Penetration Test (CPT) because of the CPT's high vertical resolution and similarities to pile penetration. These design methods incorporate the effect of this influence zone using so-called averaging methods. To assess the effectiveness of these averaging methods in predominantly sandy soils, this paper compares the Koppejan, LCPC and filter (Boulanger and DeJong) averaging methods by analyzing 41 load tests on closed-ended driven piles. The analysis indicates that the three averaging methods are more effective in predicting pile base resistance mobilized at a displacement of 10% of the pile diameter ($Q_{b,10\%D}$) compared to the maximum base resistance ($Q_{b,max}$). Overall, the Koppejan method offers the most stable and accurate predictions of $Q_{b,10\%D}$ for driven piles. However, the effectiveness of each method varies depending on specific scenarios: the Koppejan method is best suited for situations where the pile tip is in a strong layer with a weaker layer above, the LCPC method excels when the pile tip is located in a transitional zone, and the filter method is most effective in soil conditions with high variability.

Key words: *Cone Penetration Test, pile design, averaging methods*

1. Introduction

Cone Penetration Tests (CPT) are often used to estimate the pile capacity and have been shown to give reliable predictions (Schneider et al., 2008; Niazi and Mayne, 2013; Moshfeghi and Eslami, 2018; Heidarie Golafzani et al., 2020; Gavin et al., 2021). Typically, the pile base resistance (q_b) is estimated with an "averaged" cone tip resistance (q_c) value at the pile tip, $q_{c,\ avg}$:

$$q_b = \alpha_b q_{c,avg} \tag{1}$$

where α_b is a reduction factor that is dependent on the pile type and installation method. Averaging methods are calculate $q_{c,avg}$ over an influence zone that is proportional to pile diameter (D), both above and below the pile tip.

Various influence zones and calculation techniques have been developed for calculating, $q_{c,avg}$.

i. The **Koppejan method** (Van Mierlo and Koppejan, 1952), also known as the Dutch or 4D/8D method, calculates $q_{c,avg}$ using:

$$q_{c,avg} = 0.5 * [0.5 * (q_{cI} + q_{cII}) + q_{cIII}] \tag{2}$$

where q_{cI} is the arithmetic average of q_c values below the pile tip over a depth of 0.7D to 4D below the pile tip, and q_{cII} and q_{cIII} are the arithmetic averages of q_c following the minimum path rule over 0.7D to 4D under the pile tip and 8D above the pile tip respectively. A demonstration of this method can be seen in Fig. 1a.

ii. The **LCPC method** (Bustamante and Gianeselli, 1982), also known as the French or 1.5D method, uses an influence zone of 1.5D above and below the pile tip. Cone resistances are first limited to values between 0.7 to 1.3 times the average q_c. The average of the remaining values is then used as $q_{c,avg}$, as illustrated in Fig. 1b.

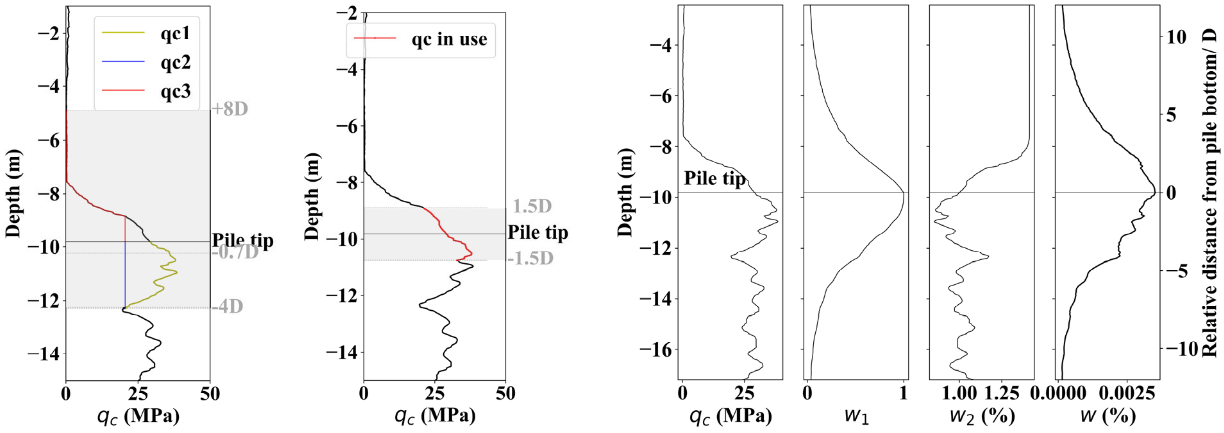
iii. The **filter method** was first proposed by Boulanger and DeJong (Boulanger and DeJong, 2018). The authors applied an inverse filtering technique to get the 'true' q_c of each layer based on the measured q_c values. The $q_{c,avg}$ based on the filter technique is the sum of w*q_c long the depth. w is calculated as:

$$w = \frac{w_1 w_2}{\sum w_1 w_2} \tag{3}$$

where w_1 is based on a reciprocal function, with higher weightings being given to depths nearest the pile tip and w_2 accounts for the relative stiffness of the point in question compared to the soil around the pile tip, giving more weighting to smaller q_c values. Fig. 1c provides a visual representation of this method. Because of the weighting system, the influence zone of the filter method can vary as a result of changes in soil layering and relative stiffnesses.

White and Bolton (2005) used the LCPC averaging method for predicting the pile base resistance and found that a constant α_b is reasonable once plunging failure can be identified as the failure criteria. However, Lehane (2019) describes a case study where the LCPC method overpredicted the base capacity of a closed-ended driven pile driven through soft clay, embedded 2.5D into a sand layer. Xu et al. (2008) conducted a database analysis and concluded that the Koppejan averaging method generally provided better predictions compared to the LCPC method. Bittar et al. (2022) applied the filter method to predict the pile base resistance and found that the method provides reasonable predictions. However, some studies often rely on specific cases, making it difficult to generalize their findings, or some are on database analyses that do not provide a detailed evaluation of each method's suitability and applicability.

In this study, a database analysis of 41 driven pile loading tests has been conducted to evaluate the performance of the three averaging methods when predicting the pile base capacity. To investigate the influence of the failure criteria on the averaging methods' performance, the pile base resistance is determined with two different failure criteria: the mobilized base resistance at a displacement of 10% of the pile diameter D ($Q_{b,10\%D}$) and the maximum base resistance mobilized during the test ($Q_{b,max}$). The advantages and disadvantages of each method are then discussed.



(a) Koppejan method (b) LCPC method (d) Filter method

Fig. 1 Demonstration of different averaging methods on CPT profile of Test No.31

2. Database

The database (Table 1) is primarily based on the ZJU-ICL database (Yang et al., 2015), as well as databases by Chow (1997), Niazi (2014) and several more recent test programs. In total, 42 static load tests on closed-ended driven piles with corresponding CPT profiles have been compiled. The maximum pile capacity ($Q_{b,max}$) for all 41 tests has been collected, and 26 of these tests also provide the base resistance at a displacement of 0.1D ($Q_{b,10\%D}$). Pile diameters range from 0.07 to 0.9m with a median of 0.3m, and the pile lengths vary from 1.83 to 45m, with a median of 9.81m. In these tests, the soil at the pile base is predominantly sand, sometimes interspersed with thin, weak layers of clay or silt.

Table 1. Database of pile load tests

No	References	Test site	Pile No	D_{eq} (m)	Pile length (m)	$Q_{b,10\%D}$ (MPa)	$Q_{b,max}$ (MPa)
	Tsuha et al. (2012)	Rio de Janeiro	Pl-4	0.50	26.50	9.08	9.17
2	Vesic (1970)	Ogeechee River	h-12	0.46	6.10		9.46
3			h-13	0.46	8.90		11.49
4			h-14	0.46	12.00		11.99
5			h-15	0.46	15.00		14.76
6	Duffy et al. (2024)	Amaliahaven	DP1	0.45	31.74	30.46	30.50
7			DP2	0.45	31.29	32.51	34.00
8			DP3	0.45	31.80	31.96	32.00
9	Gavin and O'Kelly (2007)	Blessington, Ireland	B2	0.07	3.44	18.00	18.00
10	Axelsson (2000)	Stockholm, Sweden	FSB1	0.24	12.80	2.60	2.20
11	Gregersen et al. (1973), Lunne et al. (2003)	Drammen, Norway	HSD A1	0.28	8.00	0.80	0.90
12			HSD D/A1	0.28	16.00	1.20	1.80
13	McCabe and Lehane (2006), Doherty and Gavin (2011a, b)	Northern Ireland	KG S1C	0.32	6.00	-	0.20
14			KG CE-C1	0.07	2.80	-	0.20
15			KG CE-C4	0.07	3.25	-	0.20
16	Alboom and Whenham (2003)	Brussels, Belgium	LTS B6	0.35	8.57	7.50	7.50
17	Davies (1987)	BC, Canada	UBC PRS 2	0.32	13.90	-	0.53
18			UBC PRS 3	0.32	16.80	-	3.70
19			UBC PRS 5	0.32	31.10	-	2.60
20	Lefebvre et al. (1994)	Saint Alban, Canada	SA 1-5	0.22	6.40	-	0.23
21	Garner (2007)	Salt Lake City, Utah, USA	STTS P24	0.32	12.20	-	0.46
22			STTS P14-1	0.32	12.20	-	0.44
23	Kim et al. (2009)	Indiana, USA	MCEP	0.36	17.40	4.08	4.49
24	Naesgaard et al. (2006)	Kelowna, BC, Canada	WRBB 1	0.61	45.00	7.89	8.66
25	Chow (1997), White (2003)	Dunkirk, Northern Coast, France	DK1/L1C	0.10	7.40	11.75	11.75
26			DK2/L1C	0.10	5.96	10.77	10.77
27	Lehane (1992)	Bayonne, France	LB 1/L1C	0.10	5.95	4.70	4.70
28			LB2/L1C	0.10	1.83	4.30	4.30
29	Chow (1997), White (2005)	Kallo	Pile I	0.91	9.68	8.96	8.96
30			Pile II	0.54	9.71	10.69	10.69
31			Pile III	0.62	9.82	9.73	9.73
32			Pile IV	0.82	9.80	9.22	9.22
33			Pile V	0.41	9.33	10.74	10.74
34			Pile VI	0.61	9.37	8.55	8.55
35		Hunter's Point	HP1	0.27	7.78	4.94	6.13
36	Briaud et al. (1989)	Baghdad	pile 1	0.29	11.00	4.21	4.88
37	BCP Committee (1971), Chow (1997), White (2005)	Akasaka	6B	0.20	4.00	4.30	6.37
38	Gregersen et al. (1973), Chow (1997), White (2005)	Drammen	D/A	0.28	16.00	3.43	3.61
39		Hoogzand	2-C	0.36	6.80	13.36	14.77
40	Beringen et al. (1979), Chow (1997), White (2005)	Hsin Ta	TP 4	0.61	34.30	2.92	2.92
41	Davies (1987)	BC, Canada	UBC PRS 1	0.32	11.83		0.80

3. Results and discussion

3.1. General performance

The representative $q_{c,avg}$ should ideally cover the influence of soil stratigraphy. On the other hand, the reduction factor (α_b) is considered to be constant for each pile type, although can sometimes reflect other differences between the pile and CPT cone, such as partial embedment, residual stresses and partial mobilization (Randolph, 2003; White and Bolton, 2005).

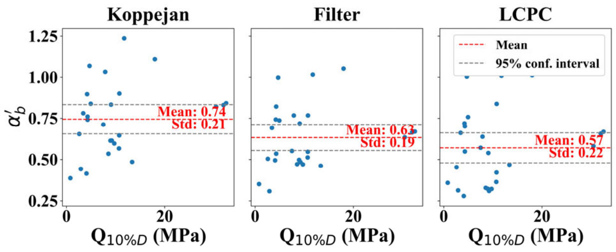


Fig. 2 Reduction factor α'_b obtained from different averaging methods under $Q_{b,10\%D}$ failure criteria

The consistency of α_b serves as an indicator of the stability of the averaging method. Fig. 2 illustrates the distribution of the ratio between $Q_{b,10\%D}$ and $q_{c,avg}$ for each test (denoted as α'_b), which aims to assess method performance in line with this criterion. Patently, the derived α'_b varies across averaging methods. As shown by the 95% confidence interval, the filter method demonstrates the least variation in α'_b, followed by the Koppejan method and then the LCPC method. The mean value of α'_b indicates that the Koppejan method tends to result in the lowest $q_{c,avg}$, and LCPC results in the highest $q_{c,avg}$.

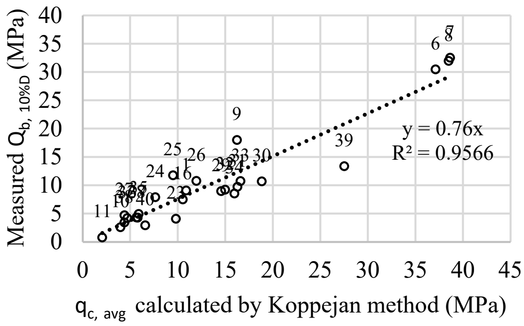


Fig. 3 Determining α_b using linear regression (Point labels represent test numbers)

However, the mean α'_b shown in Fig. 2 cannot be set as the final reduction factor (α_b) for each averaging method. Instead, α_b is obtained as the slope of the linear regression line between $Q_{b,10\%D}$ or $Q_{b,max}$ and $q_{c,avg}$. Fig. 3 illustrates this linear relationship between $Q_{b,10\%D}$ and $q_{c,avg}$ based on the Koppejan method, revealing a corresponding α_b value of 0.76.

Using $q_{c,avg}$ and the corresponding α_b derived for each averaging method, the pile base resistance can be predicted. Fig. 4 compares the measured and predicted pile base capacities across different averaging methods. The data points are evenly distributed around the diagonal, indicating no clear consistent bias in predictions using these three averaging methods. Meanwhile, data points closely aligned with the diagonal, especially for lower pile capacities (below 10 MPa). For higher capacity cases, the discrepancies become larger among the three methods. The LCPC method, in particular, tends to provide either the lowest or highest predictions. The Koppejan method and the filter method yield relatively similar results.

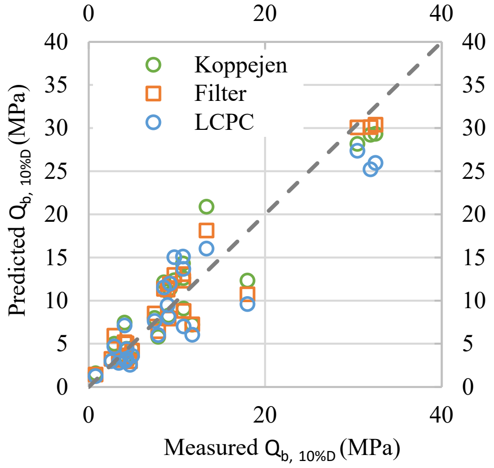


Fig. 4 Measured vs. predicted (a) $Q_{b,\ 10\%D}$

Table 2 summarizes the performance of the averaging methods under the two failure criteria. The variation of the performances is assessed by the CoV (Coefficient of Variation) of α'_b. The accuracy evaluation is based on MAPE (Mean Absolute Percentage Error) and SMAPE (Symmetric Mean Absolute Percentage Error), which measure the deviation between the calculated and measured pile base capacity ($Q_{b,10\%D}$ or $Q_{b,max}$). MAPE calculates the average of the absolute percentage differences between the predicted and actual values, while SMAPE adjusts the formula to account for both the predicted and actual values, providing a more balanced measure of accuracy. The functions are listed below:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{Q_{b\_mea}-Q_{b\_cal}}{Q_{b\_mea}}\right| \quad (4)$$

$$SMAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{2|Q_{b\_mea}-Q_{b\_cal}|}{|Q_{b\_mea}|+|Q_{b\_cal}|} \quad (5)$$

where n is the total number of data points; Q_{b_mea} is measured pile base capacity ($Q_{b,10\%D}$ or $Q_{b,max}$), and Q_{b_cal} is calculated base capacity based on three averaging methods and corresponding α_b.

According to Table 2, three averaging methods provide better predictions for $Q_{b,10\%D}$ than for $Q_{b,max}$ in terms of stability and accuracy. For $Q_{b,10\%D}$, the variation in α'_b ranges from 28% to 42%, with Q_b SMAPE values between 23.9% and 33.2%. In contrast, for $Q_{b,max}$, the variation in α'_b can reach up to 76%, with deviations up to 41.2%. Regarding the overall performance of each method, the Koppejan method provides stable and accurate predictions for $Q_{b,10\%D}$, showing the least variation in α'_b and the lowest SMAPE. The filter method performs well, ranking second to Koppejan. The LCPC method, on the other hand, does not stand out in overall performance.

Table 2. General performance evaluation of different averaging methods based on statistical parameters

Pile base resistance (MPa)	Estimation parameter	Averaging method		
		Koppejan	Filter	LCPC
$Q_{b,\ 10\%D}$	**Reduction factor α_b**	0.76	0.63	0.54
	α'_b variation (CoV)	**28%**	30%	42%
	Q_b deviation (MAPE)	27%	**26.8%**	35.9%
	Q_b deviation (SMAPE)	**23.9%**	24.9%	33.2%
$Q_{b,\ max}$	**Reduction factor α_b**	0.79	0.65	0.55
	α'_b variation (CoV)	76%	71%	**65**%
	Q_b deviation (MSAP)	**34.2%**	34.9%	39.3%
	Q_b deviation (SMSAP)	34.4%	**33.4%**	41.2%

3.2. Case analysis

The case studies highlight when each method works best, showing their effectiveness in specific situations.

3.2.1 Koppejan method

Fig. 5 shows where the Koppejan method outperforms other averaging methods when predicting $Q_{b,10\%D}$. In many of these cases, the Koppejan method still underpredicts the base resistance by up to 35%. Notably, the filter method shows similar accuracy to Koppejan, while LCPC shows the highest deviation.

Of these cases, the consistent feature observed in the CPT profiles is the presence of relatively weaker layers situated above the pile tip within 8D range. Three cases are presented in Fig. 6 (Test No. 10, 28 and 31). Fig. 6 indicates that the Koppejan method calculates the lowest $q_{c,avg}$ compared to filter and LCPC due to its large influence zone above the pile tip (8D) and application of the minimal path rule which emphasizes the weak layer influence, as demonstrated in Fig. 1.

Fig. 6a shows that no weak layers are present within ±1.5D of the pile tip, yet weak layers are present beyond 1.5D. The Koppejan method, capturing the lower q_c values of these upper weak layers, predicts a low $q_{c,avg}$ in comparison. This suggests that the weak layers above 1.5D from the pile tip may still impact the pile tip resistance. Fig. 6b and c further verify the important role of small q_c values within 8D above and 4D below the pile tip. It also suggests that the Koppejan method is particularly effective in conditions where relatively weaker layers are located above the pile tip, and the pile tip is positioned below the end of the transition zone.

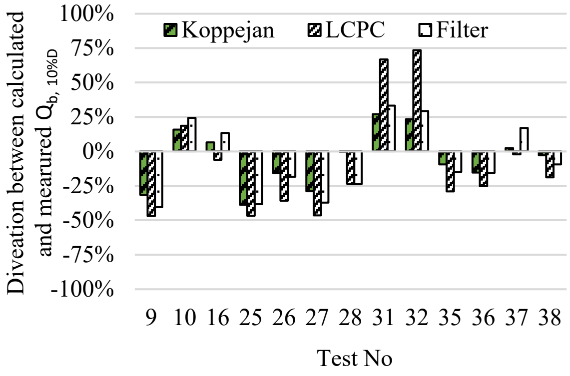
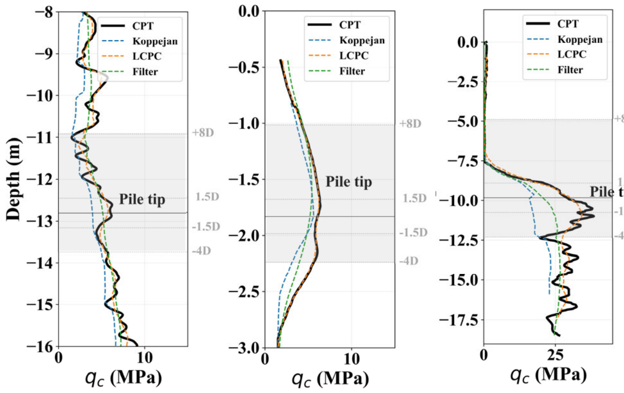


Fig. 5 Cases where the Koppejan method performs the best



(a) Test No 10 (b) Test No 28 (c) Test No 31

Fig. 6 CPT profiles of tests where the Koppejan method performs the best

3.2.2 LCPC method

Fig. 7 presents tests where the LCPC method performs better than others. For most cases listed in Fig. 7, except Test No.11, the LCPC method achieves relatively precise predictions, with deviations from the measured $Q_{b,10\%D}$ generally below 15%.

Looking at three of the well-performing examples in Fig. 8, these cases show that the piles are situated in the middle of transition zones from low to high cone resistances. Notably, $q_{c,avg}$ of the LCPC method tends to closely resemble the actual q_c values, perhaps suggesting that the q_c values within the transition zones effectively represents the combined characteristics of both the upper and lower layers. In these transitional scenarios, a smaller influence zone may be sufficient for accurately predicting pile base resistance.

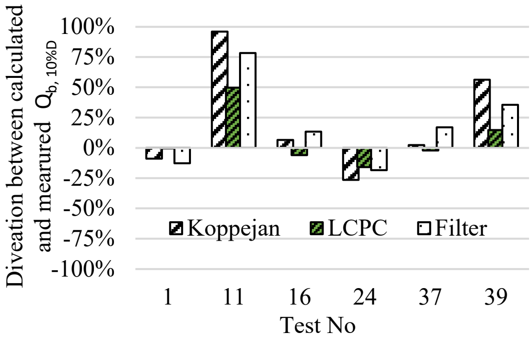
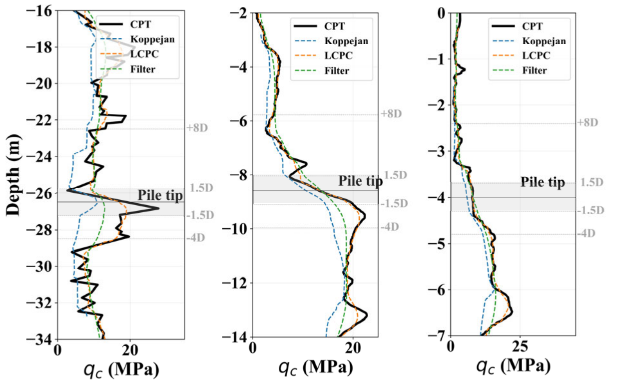


Fig. 7 Cases where the LCPC method performs the best



(a) Test No 1 (b) Test No 16 (c) Test No 37

Fig. 8 CPT profiles of tests where the LCPC method performs the best

3.2.3 Filter method

In the tests where the filter method outperforms the other two averaging methods (Fig.9), it slightly exceeds the performance of the Koppejan method and significantly surpasses the LCPC method.

The filter method is also effective in conditions similar to the Koppejan method, where soft soils overly a stronger founding layer, because it adopts a large averaging zone above the pile tip and gives more weighting to small q_c values. Moreover, the filter method is particularly well-suited for multi-thin-layered soil systems characterized by highly variable CPT profiles. Fig. 10 shows two examples of Test No.6 and No.7. Both pile tips are located deep in the strong sand-dominated layer, but with laminated thin weak layers present. The CoVs of q_c in Fig. 10 a and b are 14% and 17% respectively within the range of 10D up and below the pile tip.

In scenarios characterized by highly variable soil conditions, using a narrow averaging zone can lead to significant bias because the method relies on extreme values that skew the average. Consequently, the LCPC method often shows large deviations from the measured resistance. This observation aligns with the recommendations by Lehane et al. (2020), suggesting the application of the LCPC averaging method in homogeneous soil conditions and the Koppejan or filter methods for more variable profiles. Nonetheless, solely focusing on small q_c values can also be problematic, because thin weak layers might not be as influential as they would in the presence of thicker layers, given that adjacent thin strong layers could reinforce and stabilize the softer soil. Therefore, the Koppejan method may not perform as effectively as the filter method, because the filter method more adeptly considers the contributions of various soil layers including the thin strong layers. Fig. 10 illustrates that the values calculated by the filter method fall in the middle range.

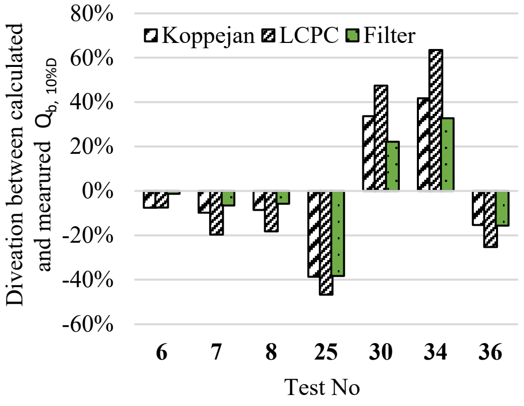
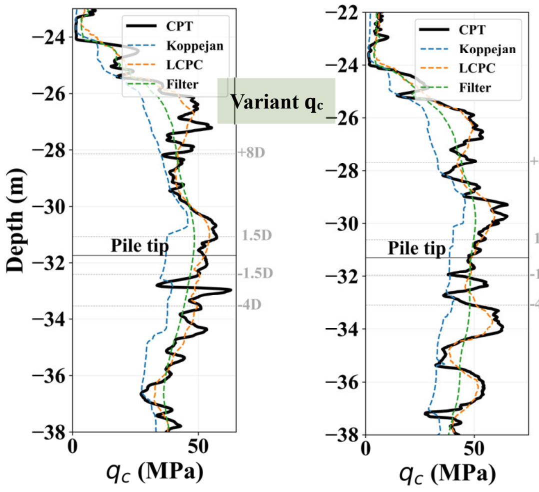


Fig. 9 Cases where the filter method performs the best



(a) Test No.6 (b) Test No.7

Fig. 10 CPT profiles of tests where the BD method performs the best (Test No.8)

4. Concluding remarks

The primary aim of this research is to evaluate the efficacy of three direct CPT-based methods, the Koppejan, LCPC, and filter methods, in predicting driven pile base resistance, using a database comprising 41 pile load tests. The findings of the study are summarized below:

- All three methods offer more stable and accurate predictions for $Q_{b,10\%D}$ than for $Q_{b,max}$, shown by lower variations in α'_b and reduced discrepancies between measured and predicted Q_b values.
- The study shows that each method tends to perform better in certain soil conditions. The Koppejan method performed best in scenarios where relatively weaker layers are located above the pile tip, and the pile tip is positioned below the end of the transition zone. The filter method also performed well in these two-layered systems, as well as CPT profiles with higher variability. Lastly, the LCPC method performed well when the pile tip is in the middle of a transition zone, benefiting from the balanced contributions of the upper and lower soil layers.

Although the study focused on a database of load tests on driven piles, averaging methods can have several implications for the design and assessment of press-in piles. For one, averaging methods improve the assessment of the pile's total capacity. Furthermore, given the similarities between press-in piling and CPT penetration, comparing press-in piling installation data with CPT data offers a means of further understanding scaling effects and sensing distances, improving both press-in piling installation prediction and CPT-based averaging methods.

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