A simplified method for predicting the load-settlement curve based on force-velocity data

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Keywords: load-settlement curve, Case Method, CAPWAP, static load test, dynamic load test

ABSTRACT: Being able to estimate the settlements that a given pile would exhibit when submitted to different static loads is important for the foundation engineer. So far, using dynamic load testing it is possible to rather accurately estimate the load-settlement curve using numeric signal matching (system identification or reverse analysis) programs such as CAPWAP. This type of analysis, however, is somewhat time-consuming, so it is rarely performed in the field. It would therefore be interesting to have a method available that would provide the engineer with a quick estimate of the load-settlement behavior in the field.

Two different approaches were investigated. The first method was based on the shaft resistance and total capacity calculated by the Case Method and on experience values for other soil parameters. These input values were then applied to a point by point numerical static analysis of the pile. The second method relied on the dynamic unloading behavior, from measured pile top force and displacement, for an estimate of the pile stiffness. In this case the load-settlement curve was modeled both as a hyperbola and as an exponential curve, according to shapes suggested in the literature. Load-settlement curves, generated using these two approaches with data from several actual dynamic load tests, were compared with the simulated load-settlement curves from CAPWAP. For several cases, the resulting curves were also compared with actual static load test results. The goal was to reach a recommendation as to the most reasonable simplified procedure for a quick estimate of the load-settlement curve using the force and velocity data from dynamic load tests directly in the field.

1 INTRODUCTION

Savings of time and money are the main reasons for the wide acceptance of the dynamic load test for the estimation of static pile capacity. Using numeric signal matching (system identification or reverse analysis) programs such as CAPWAP it is possible to rather accurately estimate the load-settlement curve of the pile. Although it does not include long term effects such as creep or consolidation, this curve is very useful to the foundation engineer for the determination of expected pile settlements under different static loads. However, the somewhat time-consuming nature of such analysis makes its performance in the field rare. A simpler and quicker method to estimate these settlements would be useful. Since the Case Method values are easily obtained during dynamic testing, their use in such a method is justified. Therefore, two different approaches for obtaining the load-settlement curve using Case Method values as inputs were investigated.

2 METHODS USED

2.1 *Method 1*

Method 1 used the Case Method values for shaft resistance and total pile capacity as inputs. The total pile capacity and shaft resistance used were the R_{MX} and S_{FR} values from the Case Method, respectively. The former is the maximum static Case Method Capacity (Rausche et al., 1985), and the latter is an estimate of the total static skin friction, based on extrapolation of the wave up curve and with a simplified correction for damping (PDI, 2004). Both values are readily available in the field. The Case damping factor used was determined by correlation with a CAPWAP analysis. The shaft resistance distribution was assumed to be triangular, with the maximum value occurring at the pile bottom. The difference between R_{MX} and S_{FR} is the toe resistance. Shaft and toe quakes of 2.54 mm and pile diameter over 60 were used, respectively. A point by point numeric static analysis was used, similar to the analysis implemented by CAPWAP (PDI, 2006), to generate an estimated load-settlement curve.

2.2 Methods 2a and 2b

Methods 2a and 2b estimated the pile stiffness using the dynamic unloading behavior from measured pile top force and displacement and Case Method values. The pile stiffness, k was estimated as:

$$k = R_{MX}/q \tag{1}$$

With q defined as the rebound distance, and calculated as:

$$q = D_{MX} - set \tag{2}$$

With D_{MX} being the maximum top displacement, found from the derivative of the velocity curve, and with the following limiting values for *q*:

$$q \geq \frac{D_{MX}}{8} \geq \frac{R_{MX} * L}{2 * A * E}$$
$$and:$$
$$q \leq \frac{D_{MX}}{2} \leq \frac{R_{MX} * L}{A * E} + \frac{D_{bx}}{60} \tag{3}$$

With A, E, L, and D_{bx} being the pile cross sectional area, pile Young's modulus, pile length, and maximum displacement at the pile bottom, respectively. The pile bottom displacement was calculated from the Wave Up (WU) and Wave Down (WD) curves, which were derived from the pile top force and velocity data. The R_{TL}, or total Case Capacity with a damping factor of zero, versus time curve was calculated as follows:

$$R_{TL(t=t)} = WD_{(t=t)} + WU_{(t=t+\frac{2L}{c})} \tag{4}$$

From the WD and R_{TL} curves, the pile bottom velocity curve was calculated as:

$$V_{toe} = \frac{2 * WD - R_{TL}}{Z} \tag{5}$$

With Z defined as the pile impedance. From this the pile toe displacement curve was derived, and D_{bx} was defined as the maximum value of this curve.

2.2.1 Method 2a

Method 2a used a modified version of Chin's equation for the shape of the load-settlement curve. The following equation was presented by Chin, F.V. (1970):

$$L = \frac{s}{C_1 * s + C_2} \tag{6}$$

where L is the load, s is the settlement, C_1 is the inverse of the limit load, which in this case was taken as R_{MX}, and C_2 is the inverse of the pile stiffness. This equation was modified so that R_{MX} would be reached at a settlement equal to D_{MX}, i.e., the pile top maximum displacement on the dynamic test. This was accomplished by altering C_1 such that:

$$C_1 = \frac{D_{MX} - R_{MX}/k}{R_{MX} * D_{MX}} \tag{7}$$

2.2.2 Method 2b

Method 2b used a modified version of Van der Veen's equation for the shape of the load-settlement curve. The following equation was presented by Van der Veen, C. (1953):

$$L = L_L*(1 - e^{-s/\beta}) \tag{8}$$

where L is the load, s is the corresponding settlement, L_L is the limit load (taken as R_{MX}), and β is a fitting parameter. In this case, the fitting parameter was determined by assuming that the derivative of equation (8), with respect to the set, is equal to the initial pile stiffness. Thus, the fitting parameter was found to be:

$$\beta = R_{MX}/k \tag{9}$$

Equation (8) was then modified so that R_{MX} would be reached at D_{MX}. This was performed by multiplying the right hand side of the equation by another fitting parameter, C_3, making the modified equation:

$$L = L_L * (1 - e^{-s/\beta}) * C_3 \tag{10}$$

The additional fitting parameter C_3 was determined to be:

$$C_3 = \frac{1}{1 - e^{-D_{MX}/\beta}} \tag{11}$$

3 PILES ANALYZED

As a first check on the performance of the proposed approaches, a total of 12 data sets were analyzed. The pile information was taken from both an existing database and recent jobs. The selected data represented a variety of soil and pile types. Of the 12 piles, 8 were bearing on a clay layer and 4 were bearing on a sand layer. Only piles less than 35 m long were chosen to minimize the effects of the pile elasticity on the load-settlement curve. The data sets chosen were required to include as minimum the soil information and the restrike force-velocity data. Preference was given to those that were accompanied by static load test data. Table 1 lists general pile and soil information.

Table 1. General information about the piles analyzed

Pile #	Diameter (mm)	Location	Type*	Length (m)	Bearing Layer
1	356	LA, USA	PPC	15.24	clay
2	356	LA, USA	PPC	15.85	clay
3	610	LA, USA	PPC	26.00	clay
4	305	Japan	H	28.00	clay
5	356	LA, USA	PCC	24.54	clay
6	762	LA, USA	PPC	17.37	sand
7	351	MO, USA	H	31.70	clay
8	346	MI, USA	H	30.00	sand
9	351	OH, USA	H	23.62	clay
10	356	OH, USA	CEP	17.68	clay
11	361	Hong Kong	H	24.80	sand
12	361	Hong Kong	H	27.50	sand

(*) – PPC = precast prestressed concrete; H = steel H-piles; CEP = steel closed end pipe

4 GRAPHICAL RESULTS

Figs. 1 through 12 illustrate the estimated load-settlement curves generated by CAPWAP and the simplified methods.

Figs. 13 through 19 illustrate the load-settlement curves from the available static load tests and the estimated load-settlement curves generated by the simplified methods for the given piles.

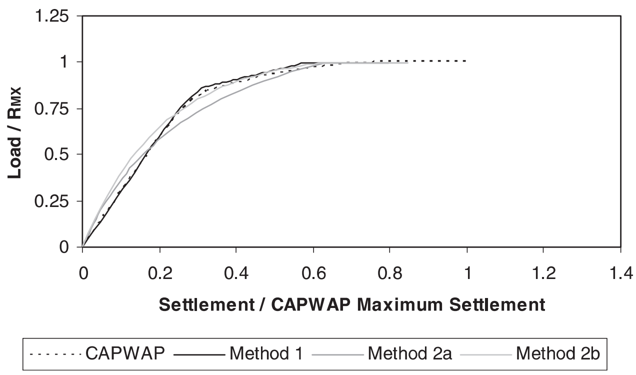

Figure 1. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #1.

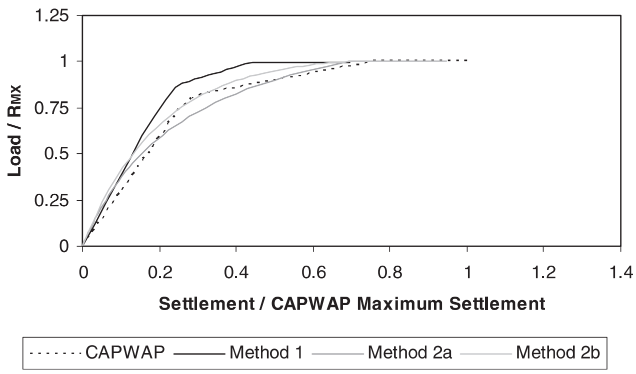

Figure 2. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #2.

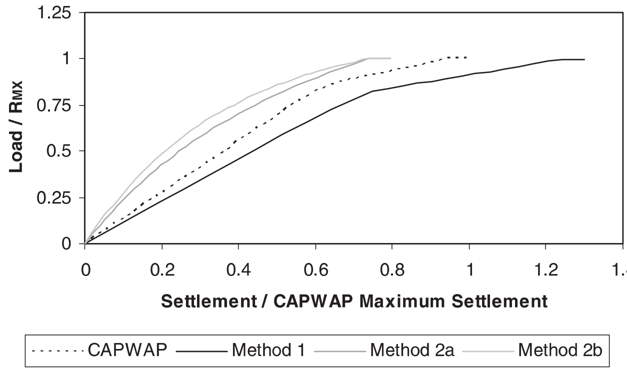

Figure 3. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #3.

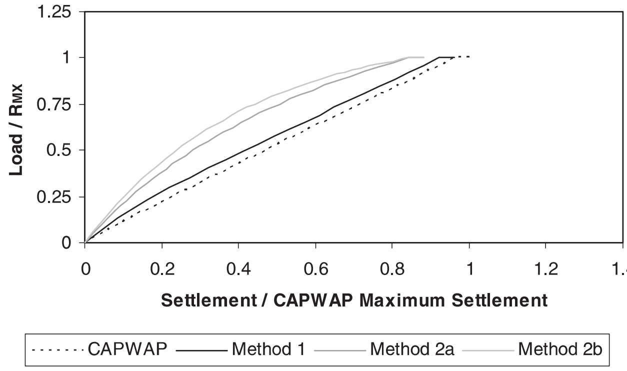

Figure 4. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #4.

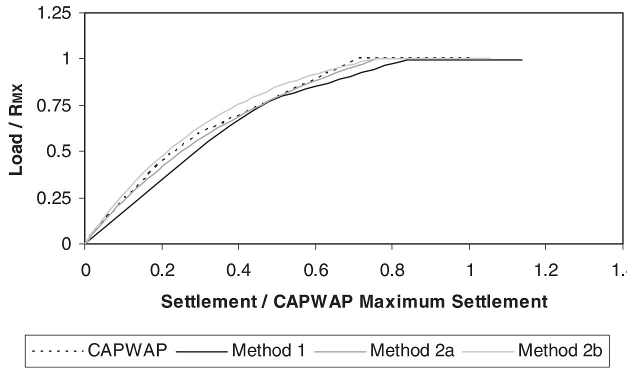

Figure 5. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #5.

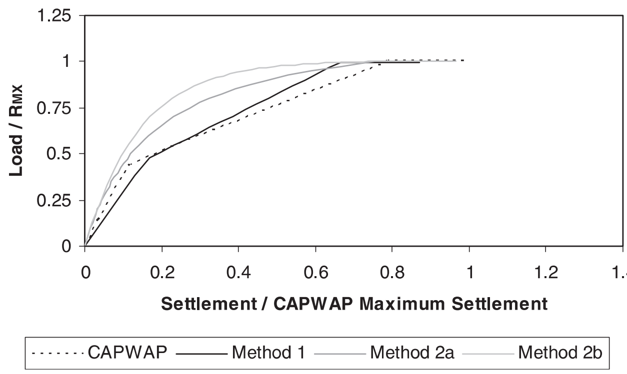

Figure 6. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #6.

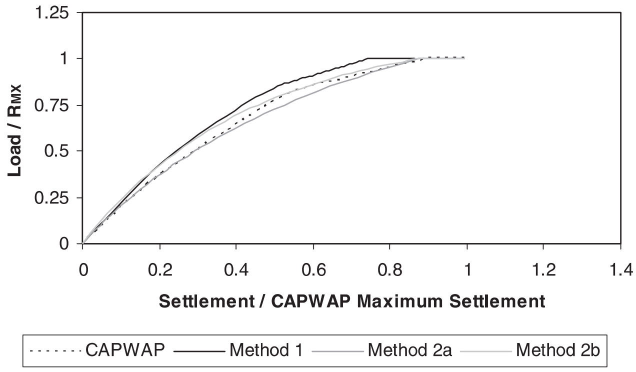

Figure 7. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #7.

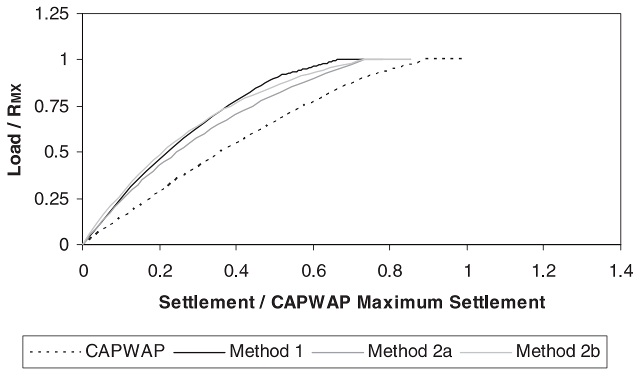

Figure 8. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #8.

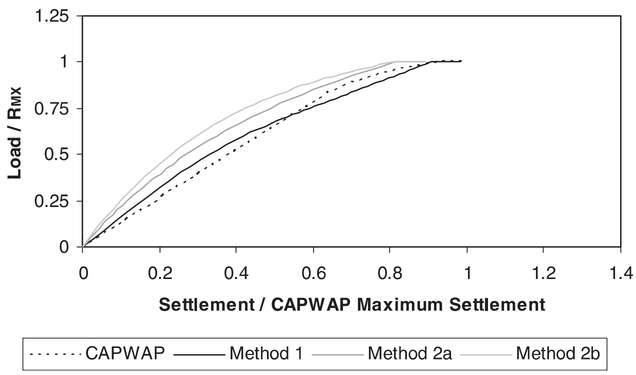

Figure 9. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #9.

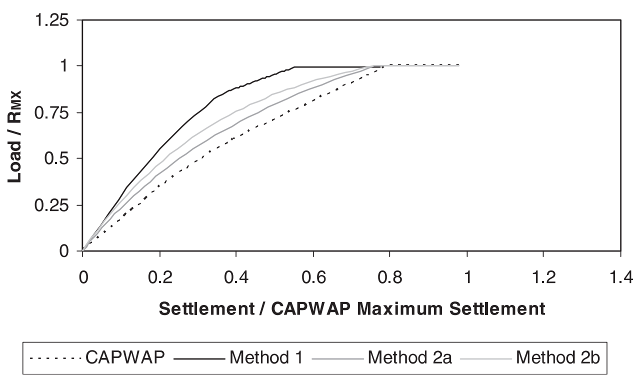

Figure 10. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #10.

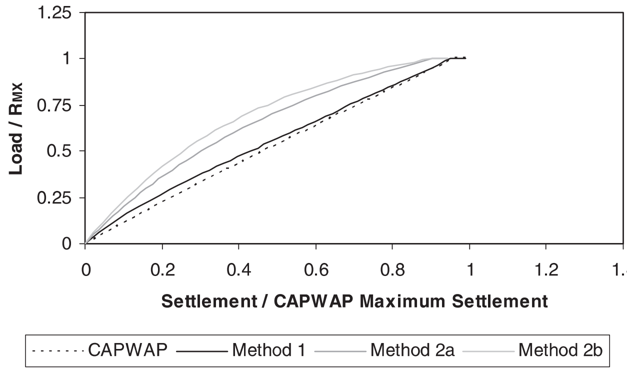

Figure 11. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #11.

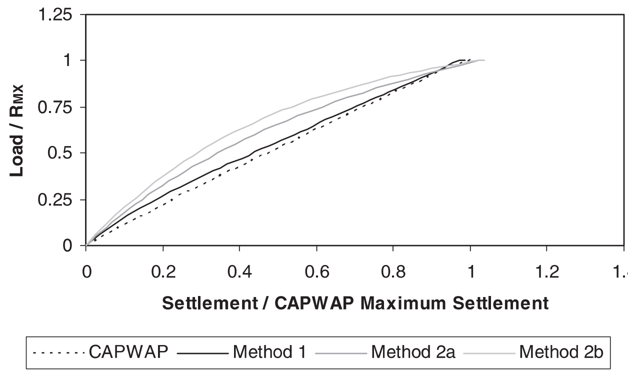

Figure 12. Comparison of load-settlement curves from simplified methods with curve from CAPWAP for pile #12.

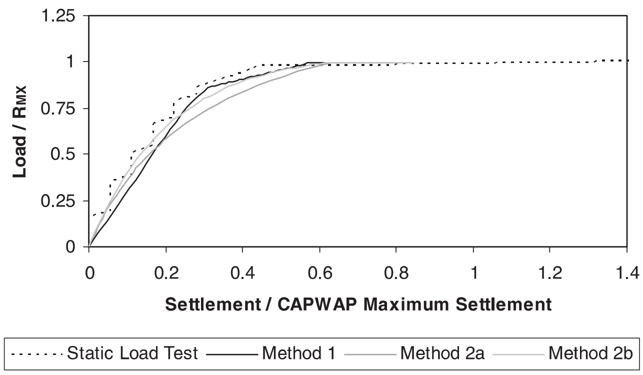

Figure 13. Comparison of load-settlement curves from simplified methods with curve from static load test for pile #1.

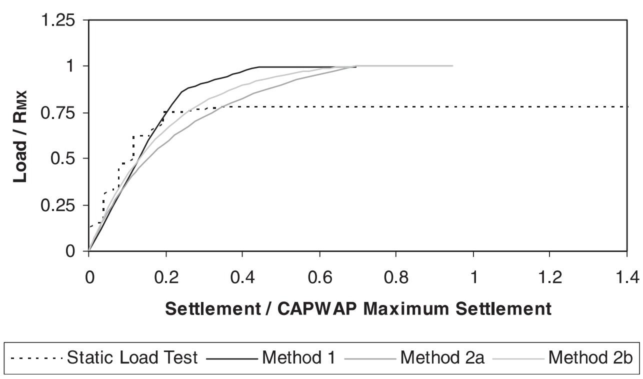

Figure 14. Comparison of load-settlement curves from simplified methods with curve from static load test for pile #2.

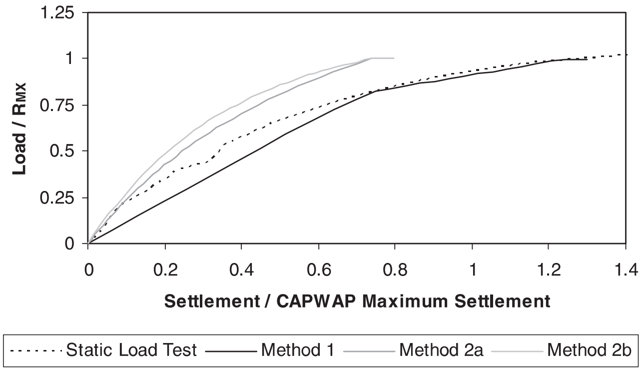

Figure 15. Comparison of load-settlement curves from simplified methods with curve from static load test for pile #3.

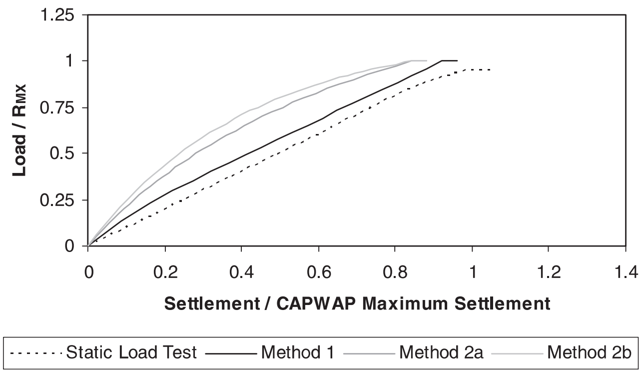

Figure 16. Comparison of load-settlement curves from simplified methods with curve from static load test for pile #4.

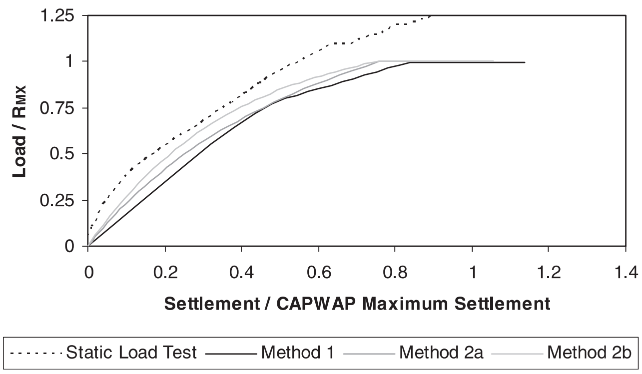

Figure 17. Comparison of load-settlement curves from simplified methods with curve from static load test for pile #5.

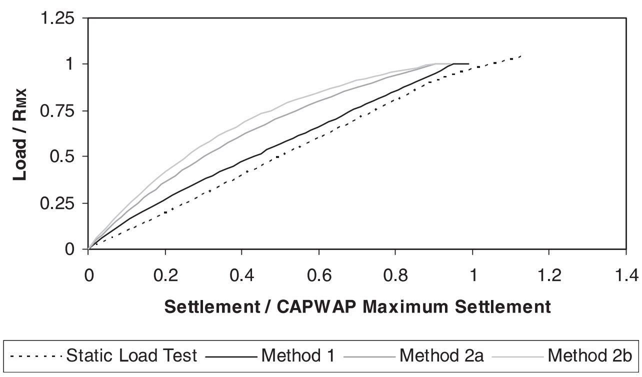

Figure 18. Comparison of load-settlement curves from simplified methods with curve from static load test for pile #11.

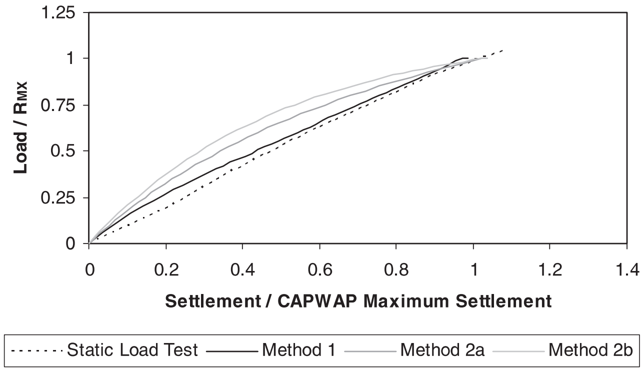

Figure 19. Comparison of load-settlement curves from simplified methods with curve from static load test for pile #12.

5 NUMERICAL RESULTS

The estimated settlements from the simplified methods were analyzed for loads of $0.25R_{MX}$, $0.50R_{MX}$, and $0.75R_{MX}$ for each pile. A match factor was defined as the estimated settlement from the simplified method divided by the settlement from the CAPWAP result. These match factors are displayed in Tables 2 through 4. The approximate methods were not numerically compared to the static load test data due to the limited number of cases.

A statistical analysis, resulting in mean and coefficient of variation (COV), was then performed

Table 2. Match factors for load equal to $0.25R_{MX}$

	Method		
Pile #	1	2a	2b
1	1.00	0.74	0.72
2	1.07	0.72	0.66
3	1.38	0.69	0.57
4	0.78	0.53	0.45
5	1.35	1.02	0.87
6	1.33	0.70	0.66
7	0.89	0.97	0.83
8	0.55	0.59	0.51
9	0.81	0.61	0.51
10	0.60	0.75	0.63
11	0.79	0.56	0.48
12	0.79	0.63	0.54

Table 3. Match factors for load equal to $0.50R_{MX}$

	Method		
Pile #	1	2a	2b
1	1.00	0.95	0.80
2	0.77	0.91	0.79
3	1.22	0.69	0.59
4	0.89	0.60	0.51
5	1.24	1.08	0.92
6	1.03	0.66	0.54
7	0.83	0.99	0.77
8	0.61	0.68	0.61
9	0.87	0.72	0.61
10	0.59	0.83	0.71
11	0.92	0.64	0.55
12	0.91	0.72	0.61

Table 4. Match factors for load equal to $0.75R_{MX}$

Pile #	Method 1	Method 2a	Method 2b
1	0.97	1.20	0.99
2	0.78	1.24	1.00
3	1.23	0.82	0.71
4	0.93	0.70	0.61
5	1.01	1.00	0.87
6	0.87	0.56	0.40
7	0.86	1.09	0.95
8	0.65	0.76	0.66
9	1.00	0.85	0.74
10	0.56	0.84	0.73
11	0.97	0.76	0.66
12	0.97	1.02	0.74

on the match factors. The results were listed separately for piles bearing on a clay layer and those bearing on a sand layer in Table 5. An ideal method would have a match factor of 1 and a COV of 0.

6 CONCLUSIONS

Two methods for estimating the load-settlement curve of a pile based on the results available in the field from dynamic load tests were analyzed. Method 1 uses the shaft resistance and total capacity calculated by the Case Method and on experience values for other soil parameters. Method 2 assumes either a hyperbolic shape (Method 2a) or an exponential shape (Method 2b) for the load-settlement curve, and estimates the pile-soil stiffness from measured pile top force and displacement. The results from those two methods were compared with the load-settlement curve predicted by CAPWAP, and with actual static load test data when available.

It was found that the two methods underestimate the sets in comparison with CAPWAP. The average range of underestimation for Method 1 was found to be relatively small, ranging between 1% and 13%. The extent of the average underestimation was greater for Method 2, ranging from 3% to 45%. However, Method

Table 5. Mean and COV of displacement match at different load levels for different bearing layers

Bearing Layer		*Clay*		*Sand*	
Method	R_{mx} level	Mean	COV	Mean	COV
1	0.25	0.99	0.28	0.87	0.38
	0.50	0.93	0.24	0.87	0.21
	0.75	0.92	0.21	0.87	0.17
2a	0.25	0.75	0.22	0.62	0.10
	0.50	0.85	0.20	0.67	0.05
	0.75	0.97	0.20	0.78	0.24
2b	0.25	0.65	0.22	0.55	0.14
	0.50	0.71	0.19	0.58	0.07
	0.75	0.83	0.18	0.62	0.24

2 was found to be more consistent for every category except sand-bearing layers at a load of $0.75R_{MX}$, with sub methods 2a and 2b performing almost equally well.

The results of this study suggest that reasonably accurate and precise load-settlement curve estimates can be obtained in the field based on a very simplified approach. Slight scaling may remove the underestimation bias from these results and make them more conservative. However, since these conclusions have been based on a small number of data sets, further research should be performed before routine applications can be recommended.

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