Static Pile Load-Movement from Dynamic Measurements

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Abstract: Static loading tests have traditionally been performed to determine the characteristics of pile load-movement relationships. Due to the expense involved and time required, this type of testing is performed on only selected piles on a very limited basis. Lower cost and speed of testing make dynamic pile testing according to the Case Method particularly attractive. These tests allow for an evaluation of the hammer-pile-soil system including pile static bearing capacity. Dynamic data may be further analyzed by the CAPWAP® Method to evaluate soil resistance distribution and predict pile load-movement relationship under static loading conditions.

This paper presents a general description of CAPWAP and its extended soil model which was most recently introduced by the authors. This soil model allows separation of static from dynamic resistance components such that a static load-set analysis from dynamic measurements becomes possible. Three case studies demonstrate this capability for different hammer, pile and soil conditions. In all three cases, both dynamic measurements and static loading tests were performed. It is concluded that dynamic testing not only can closely predict the pile static capacity, but also the relationship between applied static loads and corresponding pile

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movements. However, there are minimum requirements for high quality tests which can be expected to yield good correlations.

INTRODUCTION

The load-movement behavior of a single pile under axial loads is a function of its own flexibility and integrity, the strength and deformation characteristics of the supporting soils, pile-soil load interaction characteristics, and the nature and magnitude of the applied loads.

Traditionally, static tests have been performed to evaluate the response of piles to compression loads. Static loads are applied on the pile head and corresponding pile movement is measured. Various loading rates for Maintained Loads and Quick Tests are often used and Constant Rate of Penetration Tests (CRP) are also possible. Testing results are presented as a plot of pile top load-movement graph which is analyzed for an ultimate pile capacity. The expense involved and time required to perform a static test (particularly if instrumentation is included for shaft and toe resistance measurements) limits the test to only very few piles on major projects and perhaps none on smaller jobs. Static tests for piles with long free lengths are often extremely difficult or even impossible.

Dynamic pile testing using the Pile Driving Analyzer® (PDA) according to the Case Method (Goble et al. 1980) is frequently employed during pile installations and/or restrikes to evaluate the performance of each component of the hammer-pile-soil system. This method is based on the measurement of pile force and velocity under hammer impacts. Real time data analysis by the PDA produces information on pile stresses and integrity, hammer driving system performance and an estimate of static capacity. The relatively low cost and speed of execution of dynamic pile testing have made it a common procedure on thousands of projects annually around the world. In recent years, the application of the method has expanded to cover testing of cast-in-place shafts (Townsend et al. 1991).

Records of pile force and velocity data obtained in the field may be further analyzed by CAPWAP to evaluate pile and soil behavior. Analysis results include: static pile capacity, soil resistance distribution, and pile top and toe load-movement relationships. This paper presents the current CAPWAP models and three case histories where predicted and measured pile load-movement plots are compared.

THE CAPWAP MODEL

CAPWAP is a signal matching or system identification method, *i.e.*, its results are based on a "best possible match" between a computed pile top variable such as the pile top force and its measured equivalent. As long as the match between these two quantities is unsatisfactory, the process of iteratively changing the soil resistance parameters and then computing the pile top variable is repeated. Once this agreement is at an optimum, the analysis is finished.

THE PILE MODEL

CAPWAP calculates pile forces and motions by dividing the pile into N_p segments of uniform, continuous properties and of approximately one meter length (Fig. 1). For typical pile driving records, this segment length (and the associated time increment, Δt, discussed below) adequately represent the dynamic event in time and space. Each segment, i, has a length ΔL_i, such that its wave travel time, Δt_i, equals the analysis time increment Δt. For variable pile properties, E_i, ρ_i (elastic modulus, mass density), the wave speed, c_i, of a segment, i, is

$$c_i = \sqrt{\frac{E_i}{\rho_i}} \tag{1}$$

and the segment length becomes

$$\Delta L_i = \Delta t\, c_i \tag{2}$$

Pile segments are assumed to be uniform and linearly elastic. In the absence of cross sectional variations or soil resistance forces, the magnitude of a downward traveling wave, $F_{d,i,j}$, at time j at the top of a segment i, is equal to the wave at the top of the next lower segment, i+1, at time j+1.

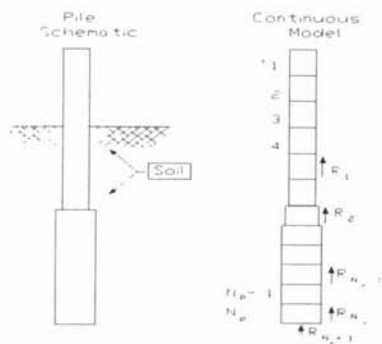

FIG. 1. The CAPWAP Pile Model

For piles with variable cross section or soil resistance, reflections occur at segment boundaries, creating upwards traveling waves, $F_{u,i,j}$, and reduced downwards waves. In the analysis, the propagation of both upwards and downwards traveling waves is tracked. Superposition of the two wave types is done according to basic wave mechanics. Forces are sums of upwards and downwards waves and velocities are the difference of the two wave types divided by the pile impedance $Z_i = E_i A_i / c_i$, where A_i is the segment's cross sectional area. From the velocity, $\dot{u}_{i,j}$, the displacement, $u_{i,j}$, is calculated using a simple Euler integration.

THE SOIL MODEL

The soil model includes N_s shaft resistance points plus an additional toe resistance. The basic Smith approach represented resistance at these points by elasto-plastic springs and dashpots requiring three parameters at each segment, i: the ultimate resistance R_{ui}, the quake q_i, and the damping factor J_i. The quake, is important for static settlement calculations. It is the distance that the pile has to move downward before the soil reaches its ultimate resistance value. The total static bearing capacity R_{ut} of the pile is the sum of the R_{ui}-values of all shaft segments and the toe.

Fig. 2 shows the extended CAPWAP soil model for shaft and toe. In order to be able to match certain signals, it was necessary to include a radiation damping model. Fig. 2 shows that the soil motion is represented by a mass and a dashpot. This "Radiation Damping" is only then necessary for signal matching when pile penetrations are small and the soil practically moves with the pile.

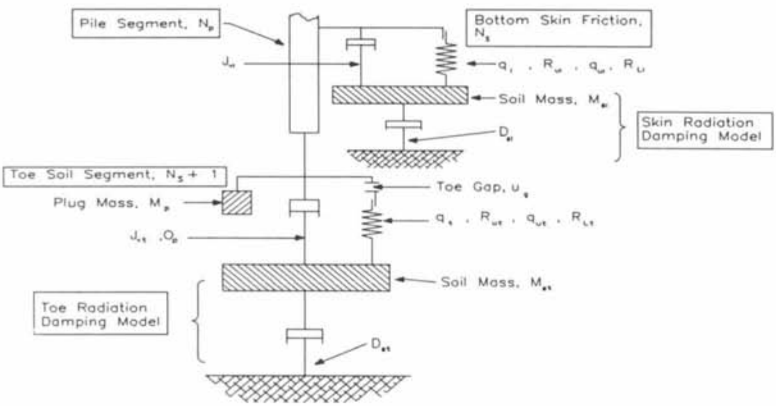

FIG. 2. The Extended CAPWAP Soil Resistance Model for Shaft and Toe

Fig. 3 illustrates the general behavior of CAPWAP's static toe resistance *vs* relative toe displacement; the shaft resistance model is similar with possibly negative resistance values during pile rebound and without a toe gap. In particular, the CAPWAP model considers:

(a) A negative static resistance limit of shaft resistance.
(b) An unloading quake, q_{ut}, and a reload level, R_{Lt}, below which unloading quakes are used after a first loading cycle.
(c) A gap, u_g, which sometimes exists under the pile toe in hard soils.
(d) A plug mass, M_p, at the pile toe; this mass is independent of the motion of the reference soil mass, M_s.
(e) Damping factors, J_v, for resistance forces which are thought to be a function of relative pile-soil velocity.

(f) A mass, M_s, and a dashpot, D_s, replacing the rigid support of the Smith resistance model with a one-degree-of freedom system.

(g) CAPWAP includes an optional residual stress analysis option like in GRLWEAP (GRL and Associates, Inc., 1993).

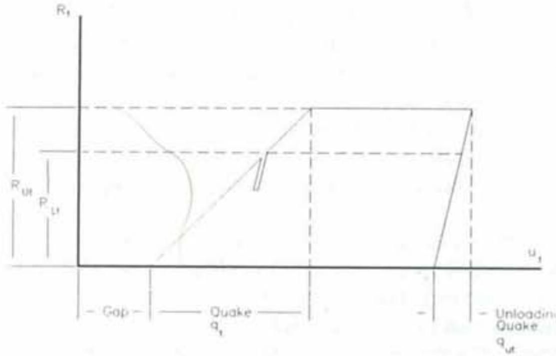

FIG. 3. Static Toe Resistance versus Relative Toe Displacement, u_t

THE CAPWAP PROCEDURE

As discussed, the shaft resistance is lumped into N_s shaft resistance forces plus one toe resistance. With 3 unknowns of the basic Smith model for each soil segment (resistance, quake and damping), the number of unknowns becomes $3(N_s+1)$. However, in most instances, it may be assumed that shaft quakes and Smith shaft damping values have equal magnitudes. Thus, there are N_s+1 unknown R_{ui} values, plus 2 unknowns each for damping and quakes. The extensions of the CAPWAP soil model add (practically as trimming parameters for signal matching) two unknowns for the unloading quakes (shaft and toe), one for the shaft resistance unloading level, two for reloading levels, and three for a toe damping option (Smith or viscous damping), toe gap and plug. Four parameters are available for radiation damping and one for the residual stress analysis option. Thus, the total number of unknowns is $N_s + 18$.

The distribution of ultimate shaft resistance forces can be directly determined from the record portion between the time of impact and the time of the first wave return. Quakes can be calculated from the time rate of resistance increase (often clearly apparent at time 2L/c after impact, *i.e.*, when the toe reflected wave returns to the pile top after having traveled along a pile of length L). Damping factors are indicated by the duration of resistance activation. The remaining quantities have to be determined from match trimming or experience.

An automatic matching option performs CAPWAP in the same way in which an engineer would go about this task. First, the early record portion is matched using the shaft resistance distribution. Next, the match at the time of first wave return is improved with toe resistance values. Thirdly, the match of the time period immediately following the first wave return is adjusted by assigning the proper total ultimate capacity. Finally, using quake and unloading values, the remaining record portion is matched. Further improvements may be achieved by varying damping values and other quantities of the extended CAPWAP soil model.

STATIC ANALYSIS

After the CAPWAP procedure has yielded a set of shaft and toe resistance parameters, a static analysis can be performed based on R_{ui} and q_i. Typically, the analysis is performed with the dynamic toe displacement *vs* time from the best match CAPWAP analysis imposed as a boundary condition at the pile toe. The equilibrium pile top force and displacement are then easily computed; mass and viscous effects are ignored. As a result, a simulated pile top force *vs* pile top displacement relationship is obtained which may be compared with standard load test results.

CORRELATIONS OF STATIC LOAD-MOVEMENT RESULTS

The pile top settlements predicted by CAPWAP from dynamic measurements are based on a dynamic event which only lasts 10 to 30 ms. It is therefore necessary to consider the limitations of this test before attempting correlations. In general, settlements of piles include both primary and secondary components. For piles driven into coarse grained or overconsolidated materials, primary settlements are probably predominate. Fine grained soils often exhibit additional settlements under sustained loads which the dynamic load test cannot predict. Additional considerations are therefore necessary, when pile tests are performed in soils with consolidation or creep potential to avoid underpredictions of settlements.

Underpredictions of load primarily occur when the dynamic tests have been performed at the end of driving when the soil was remolded or when dynamic loads caused elevated pore water pressures. Overpredictions are rarer, however, they may occur in a relaxing soil. Restrike tests after an appropriate wait period are therefore important. Furthermore, sufficient pile penetration per blow must occur during the test to "fail" the soil and cause a complete activation of all resistance forces. Non-activated resistance cannot be predicted by CAPWAP.

Poor results must also be expected if the measurements are inaccurate. This may happen, for example, if the pile material quality does not allow for an accurate calculation of forces from measured strains. Cracked concrete or yielded steel tops would preclude a linear material behavior. It is therefore important that the data is collected with accurate transducers, by an engineer experienced with the intricacies of dynamic pile testing. Under those circumstances, measurement errors can be kept below 3% even under rough field conditions. Furthermore, field processing equipment must be capable of immediately displaying the measurements in a meaningful manner such that the engineer can take immediate decisions or remedial action when needed.

CASE STUDIES

Several case studies, encompassing different pile types and soil conditions, have been reported in the literature (*e.g.*, Rausche et al. 1972; Grävare et al. 1980; Hussein and Rausche 1991). The following three cases were selected to reflect a variety of soil and pile conditions. Important details are summarized in Table 1. Fig. 4 shows soil properties along with the CAPWAP predicted resistance distributions and the measured dynamic data. The CAPWAP predicted and measured load-movement curves are presented in Fig. 5.

Table 1 also shows several important CAPWAP matching parameters. In these cases, radiation damping was not necessary for modeling (sufficient pile penetration for a clear shear failure had always been achieved under the test blows), however, variations in unloading parameters were usually needed for a satisfactory match.

Case 1: Prestressed Concrete Pile in Sandy Clayey Silt

A 305 mm square prestressed concrete pile of 16.5 m length was driven to a depth of 14.6 m into sandy and clayey silts with SPT N-values between 25 and 60. A 44 kJ rated hammer advanced the pile 200 blows per minute (BPM) at the end of driving. Three days after the installation, the pile was restruck yielding an equivalent 400 BPM blow count. The force-velocity record of Fig. 4b was then measured near the pile top. Note that the velocity had been scaled to force by multiplication with the pile impedance Z. The large force-velocity difference at time 2L/c is typical for friction piles. CAPWAP calculated the friction values of Fig. 4a. amounting to 81% of the calculated total capacity of 1870 kN. Shortly after the restrike a static quick test, lasting approximately 2 hours, was performed yielding the load-set curve of Fig. 5a. Evaluating this curve by the Davisson criterion yielded an 1840 kN ultimate capacity.

The CAPWAP analysis indicated shaft and toe quakes of 2.5 and 6.6 mm (2.5 mm would be considered normal at the toe). Calculated shaft and toe damping factors, expressed according to the Smith definition, of 0.59 and 0.39 s/m could be considered slightly lower than normal for cohesive soils. Less important trimming parameters such as soil plug (probably a soil mass trapped under the pile toe) and unloading parameters are shown in Table 1b. CAPWAP calculated and load test capacities are in very good agreement.

Case 2: Composite Pile in Calcareous Sand

A 610 mm octagonal, prestressed concrete pile with a 750 mm long H-pile steel tip protruding from its toe was driven with a 136 kJ rated hammer, operated at an 82 kJ setting, through silty sand and, below a 0.6 m thick limestone cap, into calcareous sand (SPT N = 60) to a depth of 23.8 m. Restrike records taken three days after pile installation, with the hammer at full output, are shown in Fig. 4d. They indicate a typical end bearing behavior (substantial force-velocity difference after 2L/c) with large quake (high positive velocity reflection at time 2L/c). The static test (Fig. 5b), performed prior to restrike, was again a quick test in which 15% of the expected pile capacity was applied in approximately 3 min time intervals. This test failed at 2270 kN according to Davisson's criterion and reached a maximum load of 2540 kN.

TABLE 1. Case Study Details

(a) Descriptive Parameters			
	Case 1	Case 2	Case 3
Pile material	Prestressed concrete	Concrete plus steel tip	Steel
Pile shape	Square	Octagonal, HP	HP 12×53
Pile length m (ft)	16.5 (54)	24 (79)	21.3 (70)
Pile size mm (inch)	305 (12)	610 (24)	305 (12)
Penetration m (ft)	14.6 (48)	23.8 (78)	20 (66)
Soil along shaft	Sandy and clayey silts	Silty sand	Fine sand, silt and clay
Soil at toe	Sandy and clayey silts	Calcareous sand	Clay and silt
Hammer	Conmaco 65E5	Vulcan 520	ICE 640
Blow count, EOD /m (/ft)	200 (60)	120 (36)	100 (31)
Restrike waiting time, days	3	3	2
Blow count, BOR /m (/ft)	400 (120)	80 (24)	177 (54)
Load test capacity kN (kips)	1842 (414)	2270 (510)	1260 (283)
Loading rate kN/hr (kips/hr)	1068 (240)	10680 (2400)	N/A
Penetration rate mm/min (inch/min)	N/A	N/A	0.5 (0.02)
(b) Summary of CAPWAP Results			
Capacity kN (kips)	1869 (420)	2448 (550)	1242 (279)
Shaft resistance (% of total prediction)	81	64	66
Unloading friction level %	5	100	0
Skin quakes mm (inch)	2.5 (0.10)	5.0 (0.20)	2.5 (0.10)
Unloading skin quakes mm (inch)	1.3 (0.05)	3.0 (0.12)	2.5 (0.10)
Toe quake mm (inch)	6.6 (0.26)	11.4 (0.45)	7.1 (0.28)
Unld. toe quake mm (inch)	6.6 (0.26)	4.6 (0.18)	7.1 (0.28)
Toe gap mm (inch)	0.0	1.5 (0.06)	0.0
Toe plug weight kN (kips)	1.3 (0.30)	1.1 (0.25)	1.6 (0.35)
Smith skin damping s/m (s/ft)	0.59 (0.18)	0.26 (.08)	0.85 (0.26)
Smith toe damping s/m (s/ft)	0.39 (0.12)	0.23 (0.07)	0.10 (0.03)
Radiation damping	None	None	None

Note: Case 2 driving at 66% of full energy

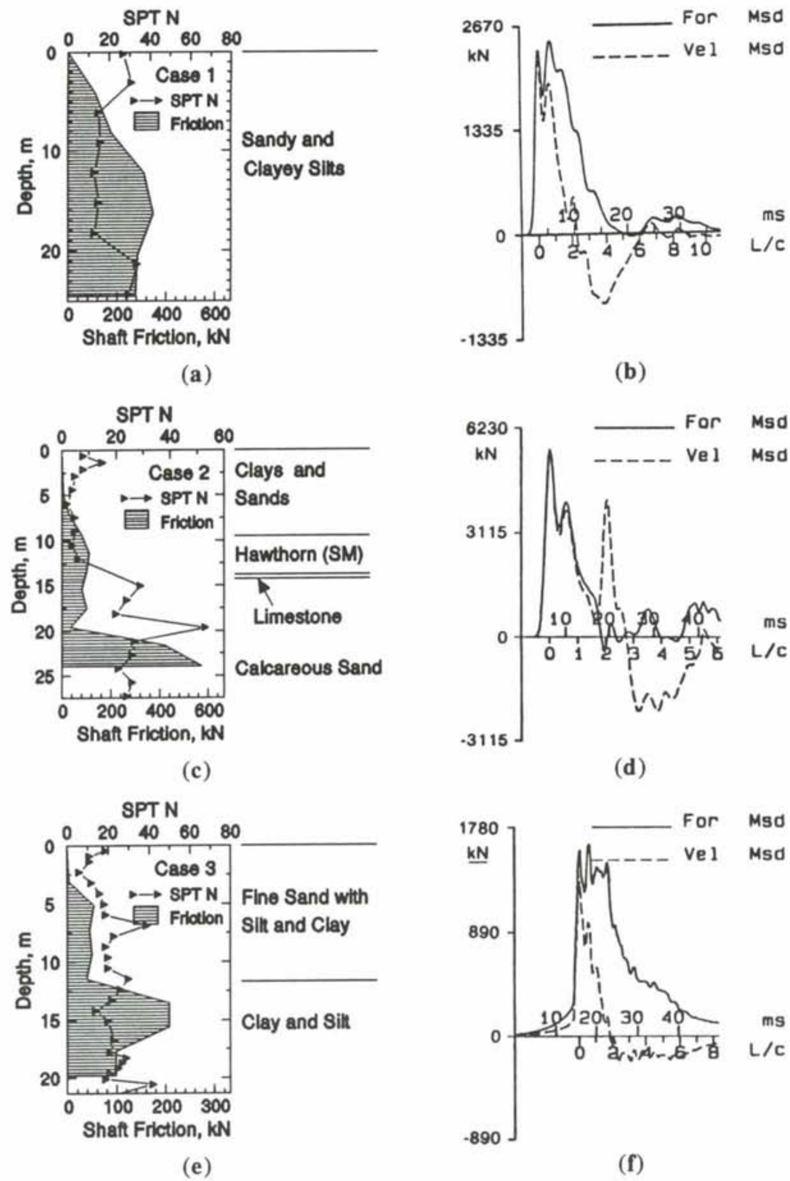

FIG. 4. Soil Properties, CAPWAP Predicted Resistance Distribution and Measured Dynamic Data

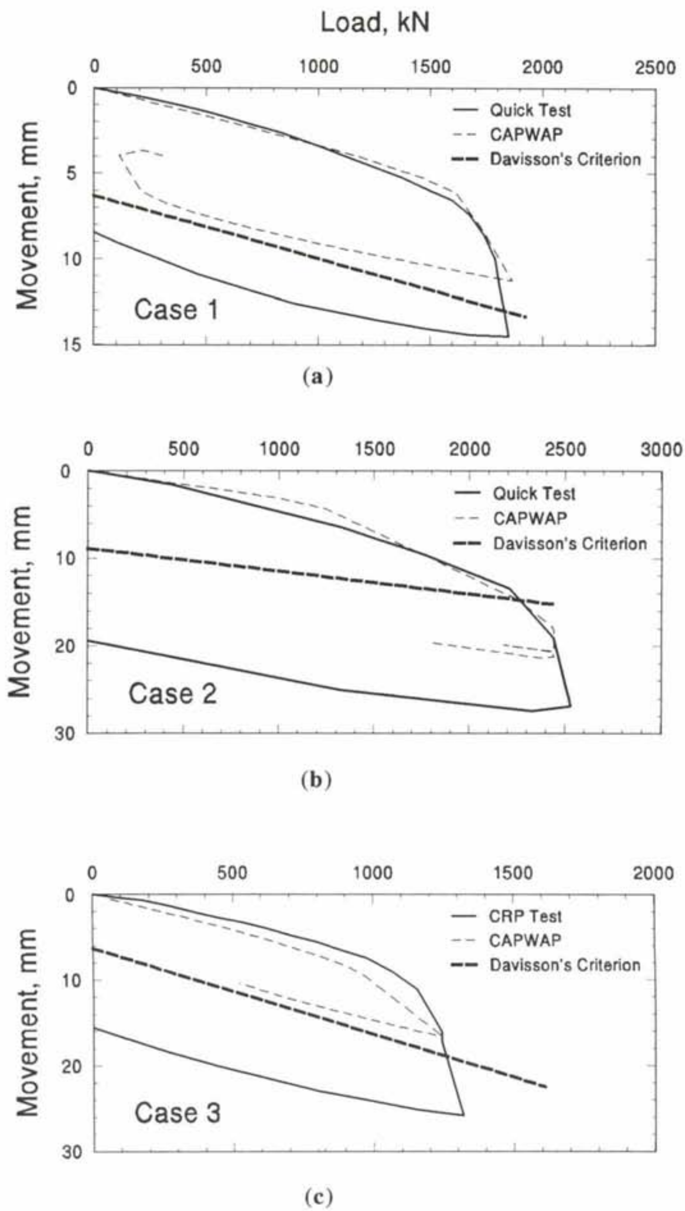

FIG. 5. Measured and CAPWAP Predicted Load-Movement

The CAPWAP calculated results indicated 64% shaft resistance (most of it near the toe as can be seen in Fig. 4c) and quakes of 5 and 11.4 mm for shaft and toe. The maximum total capacity predicted was 2450 kN.

Case 3: H-Pile in Clay and Silt

The 21.3 m long HP 12×53 (305 mm with 79 kg/m) steel H-pile was driven as part of a bridge foundation through fine sand into clay and silt. SPT N-values were in the neighborhood of 20 along most of pile shaft and toe. Under a 54 kJ rated closed ended diesel hammer, a blow count of 100 BPM was reached at a pile tip penetration of 20 m. Two days later, for the first 50 mm of penetration an equivalent blow count of 177 BPM was observed. The measurements of Fig. 4f again indicated a substantial shaft resistance by the magnitude of the force-velocity difference at time 2L/c. CAPWAP calculated 66% shaft resistance, most of it between a depth of 13 and 17 m (Fig. 4e). Apparently, a soil plug had been formed between the pile flanges allowing for a significant end bearing.

A static test was performed 4 days after the restrike at a constant penetration rate of approximately 1/2 mm per min. Davisson's failure load was reached at 1260 kN, the maximum applied load was 1320 kN with more than 26 mm pile top settlement (Fig. 5c). CAPWAP calculated the load-set curve, based on skin and toe quakes of 2.5 and 7.1 mm, again the toe quake was higher than normally assumed. In this case, a lower toe quake might have produced a slightly better agreement between the calculated measured load-set curves.

CONCLUSIONS

Dynamic pile testing is routinely performed using a Pile Driving Analyzer for evaluation of the hammer-pile-soil system including static pile capacity in the field. Further analysis of the field obtained dynamic data according to the CAPWAP Method yields information regarding soil resistance distribution and soil flexibility (quakes). These quantities suffice to predict an instantaneous load-movement behavior in many soils and for most common pile types. For three case studies, CAPWAP predicted load-set curves agreed well with those from quick tests and CRP tests.

The CAPWAP soil model is relatively complex such that measurements taken under unusual circumstances can be matched with calculated quantities. However, as demonstrated, it is often sufficient to work with the principal parameters of the Smith model. Unusual situations would include very low pile penetrations or end-of-driving situations with soil properties altered by dynamic effects. It is always preferable to perform analyses with measurements taken during restriking.

APPENDIX - REFERENCES

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