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Introduction

PILES ARE FREQUENTLY the best solution to foundation problems. However, high safety factors are commonly employed to obtain a sufficient confidence level in the foundation, given the uncertainties about hammer, soil and pile properties. By testing the integrity and bearing capacity of the pile, these uncertainties can be eliminated. This will give a more economical foundation design.

Static load testing provides one method by which a pile's integrity and bearing capacity can be verified. However, static load testing is time consuming and expensive, thus allowing for only a small number of tests on one site. To only a limited degree, therefore, can variability of soil, hammer and pile be taken into account by the static load test method.

Observations of ram stroke and pile set taken during pile driving have been used in a driving formula for quantitative analysis of bearing capacity for at least the last century. Concurrent with the more recent development of automated computing capabilities for wave equation analyses[1,2], electronic measurement techniques during pile driving were devised. Thus, the scope of pile driving observations dramatically widened and included accurate electronic measurements during the pile impact. The Case method, named after Case Institute of Technology, Cleveland, Ohio, USA, consists of measuring pile top forces and accelerations. Field or laboratory processing then provides pile bearing capacity, pile stresses and hammer energies.

In this article, the development of the Case method will be described. Its potentials will be discussed and an illustrative example will be given.

Electronic component development

After the idea of using electronic measurements on impact driven piles had been conceived in the early 1960's, two distinctly different problem areas were investigated. The first was the development of a transducer system for the measurement of high frequency impact events. Difficulties were encountered in building equipment that withstood the rugged environmental conditions on typical pile driving sites. An additional requirement was that the installation procedure should be quick and simple for routine usage.

The most successful transducer system proved to be (see Fig. 1) piezoelectric accelerometers with internal amplifier, high resonant frequencies and high *g* levels, and reusable, lightweight, bolt-on strain transducers built with resistance strain gauges. Both transducers easily adapt to any pile shape or material. In preparation for transducer attachment, holes must be drilled into the pile — for H piles, clearance holes; for pipe piles, tapped holes; and for concrete piles, holes with anchor inserts must be prepared.

Additional development work designed and constructed a field signal processor. This unit, now commonly referred to as a "Pile Driving Analyser" provides signal conditioning and amplification, and converts strain to force using the pile material and size properties. The analyser integrates acceleration to velocity, integrates the product of force and velocity to yield energy, and evaluates the force and velocity for bearing capacity. In addition, the analyser determines the extremes of all phenomena obtained such as acceleration, force, velocity and energy. The results are displayed and printed in digital form.

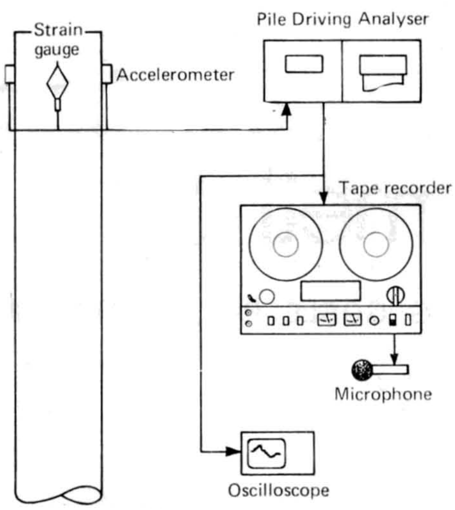

Fig. 1. Schematic layout for Pile Driving Analyser measurements and recording system

The first analyser successfully used under field conditions was completed in 1970. With improvements in electronics and interpretation techniques, additional models were built including the most recent as shown in Fig. 2.

Theoretical development

Throughout the research project a method was sought to reliably evaluate pile bearing capacity. The initially proposed idea of treating the pile as a rigid body was abandoned because of the sometimes rather strong effects of pile elasticity.

Derivation of the best approach was based on closed form one-dimensional wave solutions. Important equations are explained in Appendix *A*. In effect, the method uses the measured force and velocity at the time of impact and the pile response values of the same quantities when the stress waves returned to the pile top after reflection at the bottom. Based on travelling wave theory, the resistance force is then determined utilising damping parameters, empirically determined as a function of soil grain size to account for losses due to soil viscosity.

During the research project, correlation data was gathered for comparison of dynamic predictions with static load test results. Originally, data was obtained on Ohio Department of Transportation construction sites.

In 1970 the project was extended to cover additional states. This diversification provided data on many different pile types, sizes and materials in a wide variety of soil conditions. A summary of the efforts

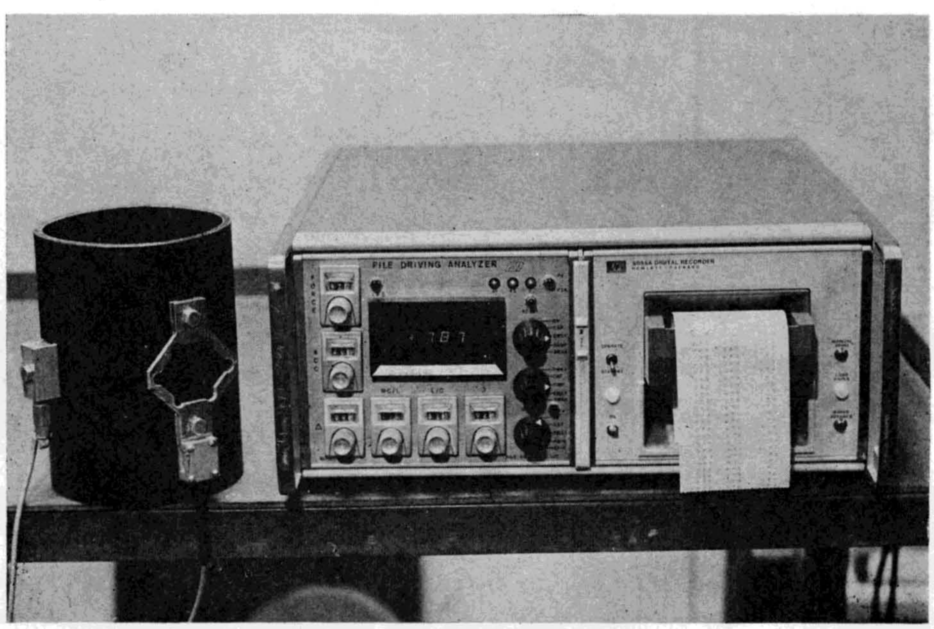

Fig. 2. Pile Driving Analyser with strain and acceleration transducers attached to pipe

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and correlations[3] of dynamically predicted and statically measured pile bearing capacities is shown in Fig. 3.

To date, the authors are still striving to extract additional results from pile top force and velocity measurements. For example, it has become possible to evaluate pile structural damage regarding its location and its seriousness at locations below grade. This technique[4] considers the hammer impact as a sonar test. Using the force and acceleration records, reflections from the point of damage are clearly apparent. Quantitative evaluations are possible because two records (force and acceleration) are taken.

Another technique determines the maximum tension stresses at locations other than the pile top where the measurements are taken. These stresses are of great importance for a safe concrete pile installation. Another newly developed technique provides pile bottom or rock stiffness values for end-bearing piles.

Probably the greatest insight into the pile and soil behaviour responses is obtained when the pile top force and velocity measurements are analysed using CAPWAP (Case Pile Wave Analysis Program, see Appendix *A*, Part II). In contrast to the Case method, CAPWAP is not dependent on a knowledge of soil type, thus providing damping factors for construction sites where no experience or static load test results exist. A digital computer and therefore office evaluation of the data is necessary if either CAPWAP or the end bearing resistance method are requested. However, tension stresses and pile damage can be evaluated in the field.

Field test procedure

Field testing is done in either of two ways. First, the pile can be instrumented and monitored while it is being driven. In this way, pile bearing capacity can be obtained as a function of penetration. In addition, stresses and hammer efficiency can be monitored for a safe and efficient pile installation; corrective measures can be taken, if necessary, and driving criteria established.

The second method would test the pile some time after installation. The pile is restruck with a relatively small number of blows. This second method has the advantage of providing bearing capacity values which include set-up/relaxation of soil strength changes after driving.

The instrumentation is attached near the pile top. The signals of force and acceleration are led through a common signal cable (Fig. 1) to the pile driving analyser. Force and velocity are monitored on an oscilloscope, thus providing pile damage criteria and a check on data quality. Acceleration and force are recorded on a magnetic tape recorder together with voice submitted observations.

For completeness, pile penetration, blow count and, if possible, hammer data such as stroke, air or bounce chamber pressure should be recorded. Although these observations are not an absolute necessity, they will aid in the establishment of a reasonable pile-driving criteria for piles not subjected to the Case method dynamic test.

Test background

Piles were driven for the extension to the Gravesend sewage works in Kent, UK in September 1978. The design load for these piles was 850kN with a safety factor of 2.0. The contractor, Balken Piling Ltd., used its precast concrete pile system consisting of regularly reinforced 275 × 275 mm (A = 756cm^2) cross-sectional segments. The total pile length was 25m. All piles were driven with a Banut 400 which is a hydraulically powered rig and hammer system. The 3 000kg ram is lifted by a hydraulic piston and the height of the completely free drop can be varied between 100 and 500mm.

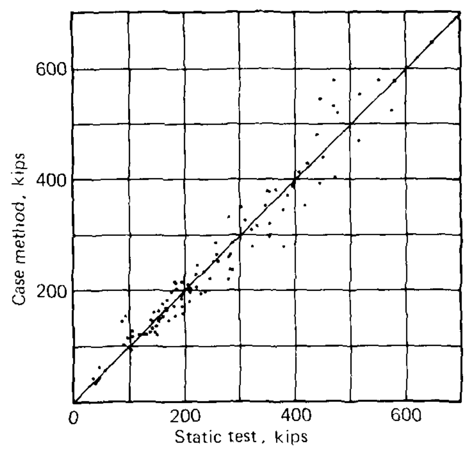

Fig. 3. Correlation of Case method capacity predictions with static load test results

In addition to the regular piling installation, the contractor drove an additional preliminary test pile which was tested dynamically during driving and then with a static proof test. This testing was performed as part of a research project sponsored by the Royal Swedish Academy of Science, The Building Research Board of Sweden and Balken Piling.

The soil profile (Fig. 4) consists of silty clay to a depth of 16m overlaying a layer of sand to a depth of 18.3m. Below was a mixture of gravel, flint and sand to a depth of 21.3m and then chalk to at least the bottom of the borehole at 24.4m. Only a few blows were necessary to drive the pile to 10m. The pile driving was at a rather uniform low blow count (Fig. 4) until the gravel layer was reached. Blow counts jumped dramatically due to the increased tip resistance in this layer. Blow counts increased further when the chalk was encountered. Refusal was met at a penetration of 1.5m in the chalk.

The standard Case method measurements of force and acceleration were made throughout the entire driving procedure. Transducers were attached 1m from the top of the pile. Results from the pile driving analyser were printed on paper tape; transducer signals were also stored on analog magnetic tape with an FM instrumentation recorder for further analysis.

This project is intended to demonstrate the power of the Case method electronic measurements during pile driving. It would be impossible, however, to show the full capabilities of this system on any one project; the measurements presented are therefore intended as only a sample. The dynamic records do not indicate the presence of any significant pile structural damage or potentially harmful tensile stresses. Therefore, readers interested in these topics must look elsewhere[4,5].

In addition to the standard Case method pile top measurements, strains were also recorded at a distance of 1m from the pile toe both during driving and during the static test.

The pile was statically load-tested to failure one day after installation and loads were measured at the top as well as at the toe. In this way, skin friction was separated from end-bearing loads.

Test results

Although results and comparisons were made in the field with the pile driving analyser, the analog tape of force and acceleration at the pile top was submitted to Pile Dynamics Inc. for further analysis by CAPWAP. Other information such as soil borings, driving logs, load test information and results of pile toe strain readings was withheld until after the CAPWAP analysis had been completed so that results obtained would be as independent as possible.

The data analysed is from the end of the initial driving to represent the service conditions of the pile at that time. Comparisons made with the static test must be made bearing in mind the soil's strength changes with time. For example, the ultimate capacity of the pile could even increase further after the load test.

The pile had a measured material wavespeed, c, of 3 428m/s and modulus of elasticity E = 28.8kN/mm^2. Typical measured force and proportional velocity (velocity × the pile impedance EA/c = force as long as no reflections from cross-section changes, pile end or skin friction resis-

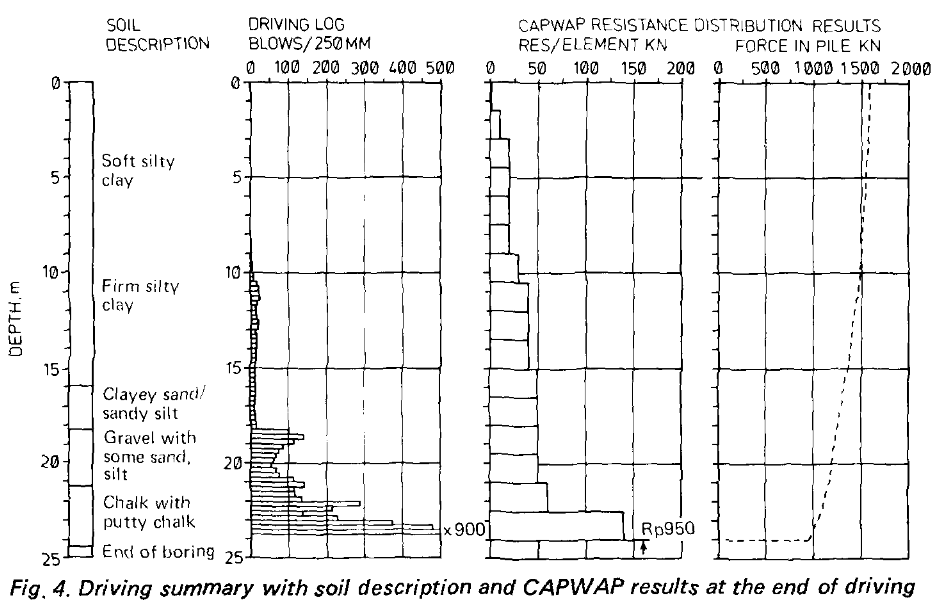

Fig. 4. Driving summary with soil description and CAPWAP results at the end of driving

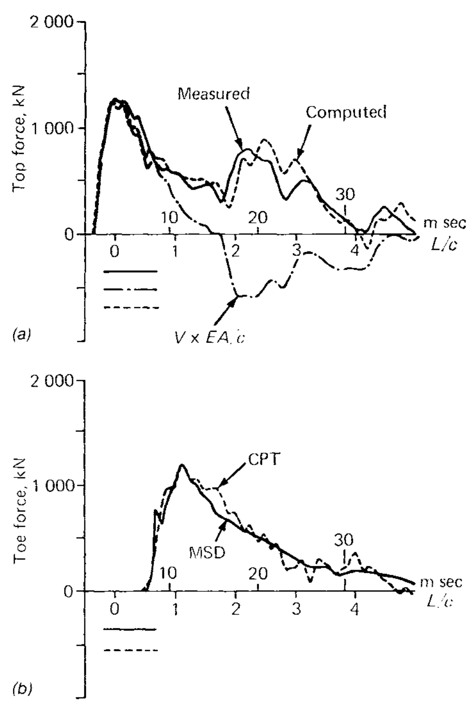

Fig. 5 (a) Measured pile top force and proportional velocity with CAPWAP computed top force: (b) Measured pile toe force with CAPWAP computed toe force

tances are present) are shown in Fig. *5a*. Using the CAPWAP procedure (Appendix *A*) with the measured acceleration/velocity as input, several static soil resistance distributions, damping constants and quakes were tried, each trial producing a computed pile top force curve. The soil parameters were varied until the match of computed and measured forces could no longer be improved within the accuracy of the lumped mass model, elastic-plastic soil resistance law and the linear viscous dampers employed. The final force match in Fig. *5a* is of fair quality.

The pile was converted into a 16-element lumped mass model with element weights and spring stiffness values given in Table I. Also, Table I presents the soil resistance values used to produce the final force match, the quakes, element resistances and element damping constants. In addition, the sum of the element resistances are given; this sum is equivalent to the force distribution in the pile when the pile is at its predicted ultimate load. The *JS* and *JT* are non-dimensional equivalent Case damping factors for the skin and toe, respectively. The *JT* toe damping constant may be converted to the dimensioned value *J* in the table by multiplying by the pile impedance *EA/c*. Similarly the *JS* skin damping constant, when multiplied by *EA/c* and distributed among the elements in proportion to the element static resistance, will give the element *J* values. The equivalent Smith damping parameters are 0.12 and 0.21 s/m for the skin and toe, respectively. The Smith damping approach is commonly used in conventional wave equation analyses.

Since a complete dynamic analysis is performed in CAPWAP, the computed top force is not the only function which can be obtained; the forces in any spring and the motion (acceleration, velocity and displacement) of any lumped mass are also determined as a function of time. Thus, a complete stress history of the pile is obtained including absolute stress minima (tension) and maxima. Since the strain at the pile toe was measured independently, the CAPWAP computed toe strain was later compared (Fig. 5*b*) with the measured one.

The CAPWAP analysis determined an ultimate failure load of 1 590kN with 950kN of this load in end-bearing. The remaining 640kN of skin friction was found to be more or less distributed uniformly over the lower half of the pile.

The resistance distribution was used with the lumped mass pile model to predict the load displacement curve during a static load test. Secondary settlements are ignored in this program. This computed load test curve is shown in Fig. 6*a*.

A static load test was performed the following day. The pile was rapidly loaded in 100kN increments and each load increment held for 16 minutes before proceeding to the next load. The maximum load which could be applied was 1 800kN. Using the strain measurement at the pile toe, a load of 910kN of end-bearing was found at the maximum 1 800kN load. The remaining 890kN was then carried in skin friction; this represents a 250kN increase in skin friction from the end of driving and may be the result of a gain of soil strength in the silty clay layers. The results of the static test are shown in Fig. 6*a* both with and without (as the predicted CAPWAP static test had assumed) creep effects. Fig. 6*b* shows the skin friction/end-bearing relationships as a function of total load.

TABLE I. GRAVESEND CAPWAP RESULTS

$JS = 0.12$, $JT = 0.30$

I	Depth, m	Quake, mm	RES, kN	SUM RES, kN	J kN/m/s	Weight, kg	Stiffness kN/mm
1	1.5	2.5		1590	0.0	286	9830
2	3.0	2.5	10	1580	1.8	286	9830
3	4.5	2.5	20	1560	2.2	286	9830
4	6.0	2.5	20	1540	2.2	286	9830
5	7.5	2.5	20	1520	2.2	286	9830
6	9.0	2.5	20	1500	2.8	286	9830
7	10.5	2.5	30	1470	4.0	286	9830
8	12.0	2.5	40	1430	4.6	286	9830
9	13.5	2.5	40	1390	5.7	286	9830
10	15.0	2.5	40	1350	5.7	286	9830
11	16.5	2.5	50	1300	5.7	286	9830
12	18.0	2.5	50	1250	5.7	286	9830
13	19.5	2.5	50	1200	5.7	286	9830
14	21.0	2.5	50	1150	6.9	286	9830
15	22.5	2.5	60	1090	7.5	286	9830
16	24.0	2.5	140	950	17.1	286	9830
Pile toe		3.1	950	0	200		

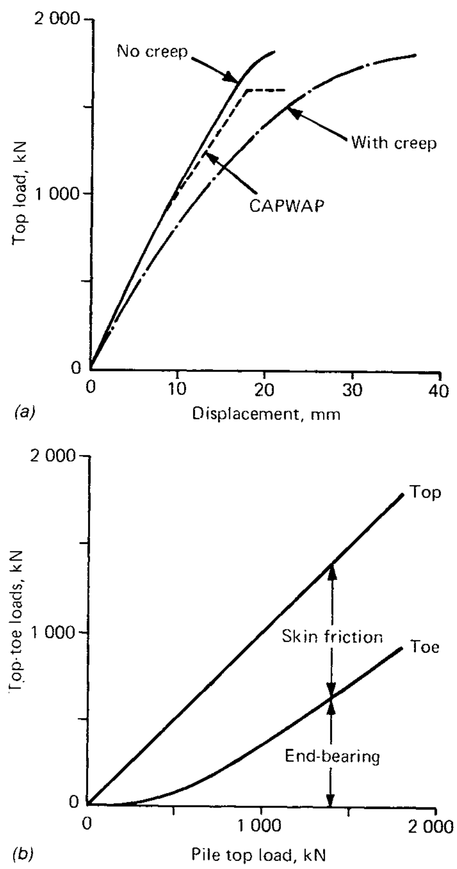

Fig. 6 (a) Measured static load test curve — with and without creep effects — and CAPWAP predicted load test curve: (b) Static test skin friction/end-bearing load distribution

The dynamic results reported above were obtained from laboratory analysis of the measured force-acceleration data with a digital mini-computer and a rather sophisticated analysis routine. Dynamic measurements taken were analysed during the actual pile driving with the pile driving analyser. Using a simpler model, the analyser predicted 1 730kN ultimate capacity, using an assumed Case damping constant of $J = 0.2$.

The analyser also determined a maximum driving stress of 0.168kN/mm², a rather safe value regarding damage due to driving stresses. The maximum measured energy transferred to the pile was 10.8kJ; assuming a drop of 450mm, the potential energy is 13.5kJ. Under this assumption, the efficiency (ratio of energy transmitted to the pile top with respect to theoretically available energy) of the Banut 400 driving rig was 80%. This is an excellent ratio considering that conventional air/steam cabled drop or diesel hammers transmit usually 50% and rarely as much as 70% of their rated energy into the pile.

The particular data analysed and presented in this article is only part of a larger construction project of Balken Piling. Further test details of this project or of the dynamic testing equipment are obtainable from Balken Piling Ltd., Birchwood Way, Cotes Park West, Somercotes, Derbyshire DE55 4PY.

APPENDIX A
Case and CAPWAP procedures

1. Case method (named after Case Western Reserve University)

Beginning in 1965, research was conducted at Case Western Reserve University in Cleveland, Ohio, to develop a method using electronic measurements taken during pile driving to predict pile bearing capacity. Pile top acceleration, *a*, and pile top force, *F*, were measured and the pile was originally assumed to be a rigid body of mass, *m*. The resistance force of the soil using Newton's Law was calculated as

$$R = F - (m)a \qquad \dots (1)$$

where *F* and *a* are functions of time. In order to eliminate resistance force components dependent on pile velocity, *F* and *a* were chosen when the pile top velocity, *v*, found by integration of acceleration, became zero.

Further studies including longer piles (more than 60ft) showed that the pile elasticity could not, in general, be neglected. Assuming uniform piles and ideal plastic soil behaviour, the following equation was derived from a closed form solution to the one-dimensional wave equational

$$R = \tfrac{1}{2}(F(t_1) + F(t_2)) + \frac{mc}{2L}(v(t_1) - v(t_2)) \qquad \dots (2)$$

where $t_2 = t_1 + 2L/c$ and t_1 ... is a selected time during the blow,
L is the pile length,
v, the velocity of the pile top, and
c, the wave transmission speed on the pile material.

Of course, the resistance, *R*, was again dependent on the choice of time t_1. Initially t_1 was also chosen as the time when the pile top velocity became zero. Later the method used t_1 as a function of soil property in terms of a fraction of $2L/c$ (time delay method).

Today the Case method models the soil resistance, *R*, as the sum of a static, *S*, and a dynamic component, *D*,

$$R = S + D \qquad \dots (3)$$

The "damping force", *D*, is obtained approximately as

$$D = J \times v_{toe} \qquad \dots (4)$$

where *J* is a damping constant, and v_{toe} the pile toe velocity.

It can be shown from wave theory that the pile toe velocity can be calculated as

$$v_{toe} = 2v_{top} - \frac{L}{mc}R \qquad \dots (5)$$

where v_{top} is the pile top velocity at time t_1.

It should be noted that t_1 is chosen at the time of the maximum velocity of the pile top (time of impact) and that *J* is often used in dimensionless form after division by mc/L. Of course, *J* is dependent on the soil type.

Eqn. *5* is approximately correct for the first $2L/c$ after the initial arrival of the stress wave at the toe. The static soil resistance, *S*, is then easily obtained by subtracting the calculated damping force, *D*, from the total driving resistance.

II. The CAPWAP method (*Case Pile Wave Analysis Program*)

Either pile top force or pile top velocity can be used in a dynamic analysis as a boundary value (both together would not lead to satisfactory results). An analysis can then be performed either in closed form or in a so-called wave analysis procedure, i.e. in a discreet form. Of course it is then necessary to describe the soil resistance forces.

The soil reaction forces are passive and up to now it has been found sufficiently accurate to express them as a function of pile motion only. It is furthermore assumed that the soil reaction consists of a static (elasto-plastic) and a dynamic (linear damping) component. In this way the soil model has at each point three unknowns (elasticity, plasticity and viscosity).

The dynamic analysis is performed in the CAPWAP method after the procedure that was introduced by Smith. This procedure divides the pile into a number of mass points and springs. In this way there are three times as many unknown soil parameters as pile elements. First, a reasonable assumption is made regarding the soil parameters, and then the motion of the pile is assumed using the measured pile top acceleration as a boundary value. Output results are not only the pile element motions and soil resistance forces, but also the *computed* pile top force, all as a function of time.

The computed and the measured pile top force will in general not agree with each other. It is necessary to improve this match iteratively by changing the assumed soil resistance parameters. Finally, a computed pile top force will be obtained which cannot be further improved. The corresponding parameters of the soil model are then considered the correct values. The results of the CAPWAP analysis then are the magnitude and location along the pile of both static and dynamic resistance forces. Static computations can be used to predict the static load test curve of the pile.

In 1970 a program was written that performed the necessary computations and decisions automatically. This program resulted in satisfactory solutions for piles which were not more than 75ft (33m) in length. For longer piles computation times became excessive. A recent program performs the computations "interactively". In the interactive mode one analysis is obtained using a minicomputer, and then the engineer determines the necessary changes of soil parameters for the next analysis. This method uses a machine with approximately 16k core memory. Of course, one also needs a plotter to draw the measured and the predicted pile top force curves. Even for longer piles it is usually sufficient to analyse 10 to 20 times.

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