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PILE BEARING CAPACITY DETERMINATION BY HIGH-STRAIN STRESS WAVE METHODS

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ABSTRACT

The development of the methods for pile static bearing capacity determination from dynamic pile tests is reviewed in this paper. Main equations of the two methods for the determination of pile static bearing capacity are then presented. The two methods are a closed-form traveling wave equation method (CASE method) and a back-analysis traveling wave equation method. Main features of the two methods are discussed. The state-of-the-art RSM instrument and software developed at the Institute of Rock and Soil Mechanics, the Chinese Academy of Sciences for dynamic pile testing is briefly described. The original data from high-strain dynamic pile tests at three sites in China obtained using the RSM instrument and another instrument are presented, compared and discussed. The advantages and limitations of the testing methods are pointed out. Issues for further research in this subject area are identified.

INTRODUCTION

In foundation engineering, pile bearing capacity determination from dynamic load testing is an important topic with practical applications (Yuan, 1988a,b). Static load testing for determining the pile bearing capacity is generally recognized to be reliable. The static load testing requires great effort and is time consuming, taking from a few hours to a number of days. The overall cost is high, depending on the length and section size of piles. In recent years, dynamic testing technique for pile bearing capacity determination, known as high-strain dynamic pile testing method, has been adopted and put into extensive applications in many countries. Main merits of the dynamic testing technique are in its being economical and taking less time and less disturbance of construction site and schedule compared to the static pile testing. The whole driving process of a driven pile can be monitored using a dynamic testing instrument. Moreover, the high-strain dynamic testing technique can be used to examine pile defects such as cracks and pile necking.

Smith (1955, 1960) studied the one-dimensional pile-driving problem based on stress wave theory. A mathematical model was developed (Smith, 1955, 1960). Generally speaking, the one-dimensional wave equation method for the analysis of dynamic pile driving is considered to be a reasonable approach and may offer advantages over static and other approaches if it can be successfully applied. Successful applications of the wave equation method require knowledge of static and dynamic soil properties, the dimensions and properties of piles, the physical properties of the pile driver and associated equipment used.

With the development in electronics and computers in the past twenty years, Rausche, et al. (1972), and Goble and Rausche (1976) developed mathematical models (methods), computer programs and hardware for pile bearing analysis based measured data of acceleration and force. The CASE method (Goble and Rausche, 1976) is one of the methods, conventionally used for the determination of pile static bearing capacity from dynamic pile testing. In the CASE method (Goble and Rausche, 1976), a closed-form solution of the one-dimensional wave propagation theory was developed using empirical correlation to static pile test results. Another method, the CAPWAP (Case Pile Wave Analysis Program) (Rausche, et al., 1972; Goble and Rausche, 1976; and Rausche, et al., 1985), is an improved version of the CASE method. The two curves of velocity *vs.* time and force *vs.* time are measured. The velocity-time curve is used as initial input for the calculation of the force-time curve. Iterations are often needed to make the calculated curve to be in good agreement with the measured results by adjusting soil parameters. This CAPWAP method can be classified into the category of back-analysis wave equation methods.

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This paper discusses (a) the closed-form traveling wave equation method and (b) the back-analysis traveling wave equation methods including a back-analysis method developed by the authors. Emphases are placed on the method, program and hardware developed by the authors. Practical applications of these methods and comparison of results are presented and discussed. Limitations of these methods are pointed out.

CLOSED-FORM TRAVELING WAVE EQUATION METHOD (CASE METHOD)

The fundamental wave equation without considering damping, is expressed as:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \pm R \tag{1}$$

where t is time; x is the coordinate along pile axis, downward positive; u is the displacement in x-direction; c is the velocity of wave propagation, $c = \sqrt{(E/\rho)}$, (E is Young's modulus of pile material and ρ is the mass density of pile material); R is soil resistance force per unit mass.

The general solution to Eq. (1) without the soil resistance R can be expressed as follows:

$$u = \psi(x - ct) + \phi(x + ct) \tag{2}$$

where $\psi(x - ct)$ is referred as downward traveling wave and $\phi(x + ct)$ is referred as upward traveling wave. By differentiating Eq. (2), the downward particle velocity $V\downarrow$ and upward particle velocity $V\uparrow$ are obtained. And using a linear elastic law for the pile material, the corresponding downward force $P\downarrow$ and upward force $P\uparrow$ can be calculated.

The measured force P_m is the sum of downward force $P\downarrow$ and upward force $P\uparrow$ while the measured particle velocity V_m is the sum of downward particle velocity $V\downarrow$ and upward particle velocity $V\uparrow$, that is,

$$P_m = P\downarrow + P\uparrow \tag{3}$$

$$V_m = V\downarrow + V\uparrow \tag{4}$$

Consider two elements in Fig. 1 with a friction force $R(i)$ acting at the boundary (i.e., Section i) of the two elements (Element i and Element $i+1$). Based on the equilibrium and continuity condition at Section i, the following equations can be obtained:

$$\begin{aligned} P_i \uparrow &= P_{i+1}\uparrow + \frac{1}{2}R(i) \\ P_{i+1}\downarrow &= P_i\downarrow - \frac{1}{2}R(i) \end{aligned} \tag{5}$$

Equation (5) indicates that when stress wave passes through Section i of a pile, the frictional resistance $R(i)$ at Section i will produce an upward force wave and a downward force wave, each of which is equal to ½$R(i)$. The two force waves due to soil resistance will superimpose to other traveling waves.

At the instant of a hammer blow acting on the pile head, there is only the downward compression wave $V(t) = P(t)/Z$, propagating toward the pile toe with a velocity c. The parameter Z is pile impedance, $Z = AE/c$, where A is pile cross-sectional area.

A set of transducers (two rings of strain gages for measuring axial force and two accelerometers for measuring acceleration) are normally installed on the pile surface near pile head at a distance of LG from pile head and L from pile toe. The transducers will receive the signals of force wave and acceleration wave when passing through them. Both the analog signals of force (P_m) and acceleration are converted to digital data through an analog-to-digital converter. The digital data of acceleration are integrated numerically to get the time-history of velocity (V_m) of the pile at the instrumented section.

By using the force P_m and velocity V_m from the measured force and velocity curves, the total frictional resistance, $R(t^*)$ for a chosen time t^*, of the pile can be calculated from the following equation:

$$R(t^*) = \frac{1}{2}[P_m(t^*) + P_m(t^* + \frac{2L}{c}] + \frac{Z}{2}[V_m(t^*) - V_m(t^* + \frac{2L}{c})] \tag{6a}$$

where the $t^* + 2L/c$ can be written as $t^* + \Delta t$ where $\Delta t = 2L/c$, which is the time when the wave travels to the pile toe and returns back to the location of the transducers. Equation (6) is the fundamental equation of the CASE method (Goble and Rausche, 1976).

Since $c = \sqrt{(E/\rho)}$, $\Delta t = 2L/c$ and $Z = EA/c$, the $Z/2$ in the second item on the right side of Eq. (6a) can be written as $Z/2 = \rho AL/\Delta t = M/\Delta t$, where $M = \rho AL$ which is the total mass of the pile below the transducers. Thus Eq. (6a) can be written as:

$$R(t^*) = \frac{1}{2}[P_m(t^*) + P_m(t^* + \frac{2L}{c})] + M \times a_{avg} \tag{6b}$$

where $M = \rho AL$ and $a_{avg} = [V_m(t^*) - V_m(t^* + 2L/c)]/\Delta t$ which is the average acceleration of the pile mass below the transducers. Therefore, Eq. (6a) or Eq. (6b) means that the total resistance consists of the average of two force values measured at a time interval $2L/c$ apart (L is the length between the transducers and the pile toe), plus the average acceleration over the same time interval multiplied by the pile mass.

Total resistance $R(t)$ is assumed as a sum of static resistance $R_s(t)$ and dynamic resistance $R_d(t)$, or $R(t) = R_s(t) + R_d(t)$. The dynamic resistance $R_d(t)$ is assumed to be expressed by:

$$R_d(t) = JV_{toe} \tag{7}$$

where J is a damping coefficient, V_{toe} is the velocity of the pile toe. It can be found that the velocity V_{toe} is

$$V_{toe} = \frac{1}{Z}[2P(t^*) - R(t^*)] \tag{8}$$

where $P(t^*)$ and $R(t^*)$ are total force in the pile and total pile resistance at a chosen time t^*. The static resistance $R_s(t)$ can then be expressed as, for a chosen time t^*,

$$\begin{aligned} R_s(t^*) = {} & \frac{1}{2}[P_m(t^*) + P_m(t^* + \frac{2L}{c})] + \frac{Z}{2}[V_m(t^*) - V_m(t^* + \frac{2L}{c})] \\ & - J_c[2P(t^*) - R(t^*)] \end{aligned} \tag{9}$$

where $J_c = J/Z$ which is called as the CASE damping coefficient.

The maximum mobilized soil resistance, R_s, is considered to be the value close to the real static soil resistance as:

$$R_s = MAX[R_s(t^*)] \qquad for\ 0 < t^* < \frac{2L}{c} \tag{10}$$

Rausche, et al. (1985) suggested J_c values for different soils, mainly based on the comparative study on predominantly end bearing piles. Law (1996) compared the static bearing capacity calculated using CASE method to the measured static bearing capacity for 9 piles (20 m to 28 m long) at a site of Tin Shui Wau Area 13 Phase 1 Project. Law found that the J_c values were in the range 0.3 to 0.4.

The equations for CASE Method are derived based on the assumptions of a uniform pile cross section, linear elastic pile behavior, no shear stress in the pile and rigid plastic soil resistance. The latter of these assumptions cannot be satisfied, since internal pile damping is not included. The pile capacity may not be fully mobilized at time $t + 2L/C$. For determination of ultimate pile capacity, enough penetration is needed to allow the resistance on pile surface and pile toe to be fully developed. In general, 2 mm of final penetration is required for practical pile capacity determination. For solid concrete pile, the hammer weight should not be less than 8% of the pile weight. However, a larger hammer weight (20% or more the pile weight) is recommended for more reliable bearing capacity determination.

A pile with a large number of cracks can result in more wave reflections and refraction. Therefore, Eq. (9) and Eq. (10) cannot be used for determining R_s in this case. When hammer weight is too small, compared to pile capacity, conservative predictions can be made. Because large energy is required in pile capacity testing using CASE method, the practical application of this method is limited, particularly for those large bored piles.

The CASE damping coefficient, $J_c = J/Z$, is an approximate assumption. It is obvious that the damping coefficient, J in Eq. (7) is related to soil behavior. But J_c is dependent on acoustic characteristics of a pile. For different pile materials the CASE damping coefficient J_c should have a different value. Therefore, for local applications, J_c values shall be estimated based on the correlation of static bearing capacity determined from dynamic pile tests to the capacity from static pile tests on local soils and pile materials.

BACK-ANALYSIS TRAVELING WAVE EQUATION METHOD

Despite of the assumptions made in the above closed-form traveling wave equation method, what is obtained is the estimated total static bearing capacity without any information regarding the soil resistance distribution on the pile surface and toe, and the pile deformation. The CASE damping coefficient, J_c, is highly empirical. The values suggested are pile dependent and site specific. How to determine the soil resistance distribution, load-deformation behavior and to best estimate J_c have been an area of intensive research in the past decades.

Rausche, et al. (1972) suggested a back-analysis procedure based on Smith's discrete model (Smith, 1955) and developed a CAPWAP computer program for the back-analysis (Rausche, et al., 1985). The Newmark β method was applied for solving the dynamic equilibrium equation with $\beta = 1/6$. This is actually a linear acceleration integration process in dynamic finite element method. The computation using this method is slow. The element length of the pile shall be sufficiently small in order to get reasonably accurate results.

The CAPWAP was re-written, re-named as CAPWAPC, based on a continuous pile model and traveling wave theory (CAPWAP manuals 1984, 1993). The authors and team members (Liu, et al., 1993) developed a computer program, named RSM-PileStar, which is also based on the continuous pile model and traveling wave theory. This section introduces the basic theory, numerical approach, and newly developed RSM hardware and an RSM-PileStar program.

In this method, the pile is divided into a number of elastic elements. For different size of pile cross-section area, pile element lengths are different. However, the length of each pile element should be chosen so that the time needed for the wave to pass through each pile element must be equal. For each pile element, the forces are assumed to act on the bottom of each element. The change of acoustic impedance for each element occurs at the interface of the elements. No wave distortions within the elements during wave propagation are assumed.

The upward wave force $P{\uparrow}(i, j)$ (i = index for pile elements, j = index for time steps) and downward wave force $P{\downarrow}(i, j)$ for i-th element at time $t = j\Delta t$ can be expressed as follows

$$P\uparrow(i,j) = T\uparrow(i)[2P\uparrow(i+1,j-1) - P\downarrow(i-1,j-1) + R(i,j)] + T\downarrow(i)P\downarrow(i-1,j-1) \tag{11}$$

$$P\downarrow(i,j) = T\downarrow(i)[2P\downarrow(i-1,j-1) - P\uparrow(i+1,j-1) - R(i,j)] - T\uparrow(i)P\uparrow(i+1,j-1) \tag{12}$$

where

$$T\uparrow(i) = \frac{Z_i}{Z_i + Z_{i-1}} \qquad T\downarrow(i) = \frac{Z_{i+1}}{Z_{i+1} + Z_i} \tag{13}$$

Z_i is acoustic impedance of Element i (Fig. 1).

The computed force $P_c(j)$ at the location of transducers is given by following equation:

$$P_c(j) = ZV_m(j) + 2P\uparrow(2,j-1) \tag{14}$$

In Eqs. (11-13), i is set to be 2 for the element just right below the transducers (as Element 2). Thus in Eqn.(14), $V_m(j)$ is the velocity measured by the transducer at time $t = j\Delta t$.

The velocity and displacement of different pile sections can be expressed as follows:

$$V(i,j) = \frac{P\downarrow(i,j)}{Z_i} - \frac{P\uparrow(i,j)}{Z_{i+1}} \tag{15}$$

$$u(i,j) = u(i,j-1) + \frac{\Delta t}{2}[V(i,-1) + V(i,j)] \tag{16}$$

The soil models used in CAPWAPC program and in RSM-PileStar program for the calculation of $R(i, j)$ in Eq. (11) and Eq. (12) are similar to that proposed by Smith (1955). An ideal elastic-plastic model is commonly used with at least two basic model parameters, i.e. limit soil resistance R_U and the quake Q_U (the elastic deformation up to the limit R_U). The stiffness modulus at the soil/pile interface is the ratio of R_U/Q_U. More model parameters were introduced in CAPWAPC (CAPWAP manual 1993) to consider unloading limit, soil/pile loading gap, and different unloading/reloading stiffness. Since the pile toe cannot withstand tension, the unloading limit R_{UL} may be set to zero, i.e., $R_{UL} = 0$.

The total soil resistance $R(i, j)$ is divided into two parts, i.e. the static soil resistance $R_s(i, j)$ and dynamic soil resistance $R_d(i, j)$. The dynamic soil resistance $R_d(i, j)$ is expressed by:

$$R_d(i,j) = J_s(i)\,V(i,j) \tag{17}$$

where $J_s(i)$ is the damping coefficient, which has probably a different value at different position.

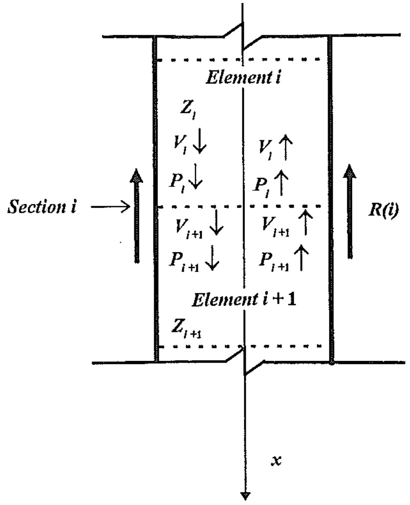

Fig. 1 Elements, Section *i*, Waves and Lateral Resistance

In addition to the parameters involved in the soil model described above, two more parameters, that is, the pile toe mass, M_{sm}, and pile toe damping coefficient, J_{sm}, are considered in both CAPWAPC and RSM-PileStar programs. A mass point is attached to the pile toe to simulate the movement of the soil mass at the pile toe. Thus, there is a soil mass inertia force $R_{sm}(j)$ acting at pile toe:

$$R_{sm}(j) = M_{sm}\,[V(mp, t) - V(mp, t-1)] / \Delta t \tag{18}$$

where $V(mp, j)$ is the velocity of pile toe point (i-index is mp) and Δt is a time step.

For simulation of energy dissipation around the pile toe, a soil damper can be put beneath the pile toe with the damping coefficient J_{sm}. The damping resistance $R_{dm}(j)$ is expressed by:

$$R_{dm}(j) = J_{sm}\; V(mp, t) \tag{19}$$

The objective is to minimize the absolute difference between the computed force and the measure force, i.e.:

$$P(x) = \sum_{j=1}^{N_{time}} ABS[P_c(x, j) - P_m(x, j)] \tag{20}$$

where $x = x\,(R_U(i), Q_U(i), J_s(i), R_{toe}, Q_{toe}, M_{sn}, J_{sm})$ for $i = 1$ to N_{pile}. The index N_{pile} is the total number of pile elements and the index N_{time} is total number of time steps. The total number of unknowns is $3N_{pile} + 4$.

An optimization computational procedure is proposed by authors to back-calculate the unknown parameters by minimizing Eq. (20). The soil parameters are adjusted to minimize the difference of measured and computed results in the time interval of $4L/c$. The purpose for adjusting soil parameters is to obtain better agreement between the computed and measured waves.

INSTRUMENT FOR PILE BEARING CAPACITY TESTING

In order to back-calculate the unknown parameters, two sets of data are required, i.e., the time-histories of velocity and force. The Institute of Rock and Soil Mechanics (IRSM) of the Chinese Academy of Sciences started the development of the instrument for dynamic pile testing in early 1980's. A series of RSM instruments have been developed. The instrument developed for pile bearing capacity testing is RSM-CASE system. The RSM-CASE system has four parts: (a) the hardware (RSM-24FD - instrument), (b) transducers, (c) a notebook computer and (d) the computer program (CASE - software) (Liu, 1995). The CASE software is used for two purposes: (a) for data acquisition and basic computation such as numerical integration, numerical fast Fourier transformation, etc. and (b) for evaluation of the static bearing capacity using the closed-form traveling wave equation method and the assessment of the pile integrity.

The RSM hardware consists of four functional parts: (a) charge amplifier, (b) signal filter, (c) signal amplification, and (d) analog-to-digital conversion. The hardware in RSM-CASE system is the same as that in RSM-PRT system for low-strain pile integrity testing. The difference between RSM-CASE and RSM-PRT systems is that (a) two accelerometers are installed near the pile head, normally 1.5 diameters of the pile and installed in opposite and (b) two rings of strain gages are installed at the same section as the accelerometers also in the opposite position. A brief description of the four functional parts is given below.

Charge Amplifier

The specially designed charge amplifier is an electronic device with two special actions: (i) to amplify the charge signals measured using an accelerometer and to convert them into voltage signals and (ii) to provide a low input resistance and a high output resistance for the suitable resistance adaptation between the output terminal of accelerometer and the input terminal of the instrument. The voltage value of the charge-amplifier's output is directly proportional to the acceleration value measured with an accelerometer attached at pile head.

Signal Filter

Signals obtained from a transducer during field testing contain mechanical and electronic noises. Therefore, the signals have to be filtered with a low-pass filter and a high-pass filter before being amplified and being converted into digital data. A low-pass filter can delete noises of high frequencies. A high-pass filter can eliminate low frequency noises such as vibrations of the field, pile/soil combination, and the zero-shift of accelerometer's output. The filter designed with an electronic circuit is called analog-filter. The RSM-CASE computer program includes a special sub-program as a digital-filter.

Signal Amplification

Because the energy of each hammer blow transferred to pile head varies in a very large range, it is difficult to select the most suitable gain for an amplifier manually. If the gain is fixed during signal sampling process after each blow, the output signal of the amplifier may sometimes be too weak to be observed or overflow. The floating-amplifier adopted in the RSM-CASE system can always automatically select the most suitable gain at each sampling time interval during the whole testing process. The events of signals being too weak to record and overflowing output will never occur.

Analog-to-Digital Conversion

The analog-to-digital converter used in the RSM-CASE system is a A/D integrated circuit with 16 bits. The floating-amplifier mentioned in signal amplification produces a gain-code varying from 0 to 8. Liu (1995) showed that the final result of A/D conversion using the floating-amplifier in RSM-PRT system had a dynamic range of 24 binary bits. The fastest sampling rate of the A/D conversion is 10μs. Paquet (1992) recommended a minimum of 50μs of sampling rate for detecting a 0.4 m apart of two reflectors (defects). The sampling rate of the RSM-CASE system is 10μs and is good for detecting a 0.08m apart of two reflectors. The transducer used for measuring acceleration at pile head is a type of piezo-electric devices called piezo-accelerometers. The data obtained and stored in the notebook computer can be used by RSM-PileStar program to carry out back-calculation of those unknown parameters in Eq. (20).

FIELD APPLICATIONS AND COMPARATIVE STUDY

Closed-Form Traveling Wave Equation Method

Both RSM instrument and PDA instrument (PDA, 1993) were used to measure the bearing capacity of piles at sites of Panyu city of Guandong Province, China. The measured data and curves are not presented in this paper. A summary of the main parameters and results for pile No. 100 and pile No. 96 are presented in Table 1. F_{max} is the maximum impact force from hamper, D_{max} is the maximum settlement at pile head, WE_{max} is the maximum energy transferred to the pile, and R_s is the maximum mobilized static resistance. The piles were precast and prestressed hollow circular concrete piles installed using a diesel hammer. The soil was sandy clayey silt. The CASE damping coefficient J_c was 0.4 used in both PDA CASE analysis and RSM CASE analysis.

It is seen from Table 1 that the main results measured and analyzed using RSM instrument and the CASE method are similar to those measured using PDA instrument and the CASE method (PDA, 1993). The calculated static pile capacity using data from RSM instrument is about 10% larger than the value using PDA instrument.

Back-Analysis Traveling Wave Equation Method

Main results of dynamic pile testing on pile No. 13 in Foshan city of Guandong Province, China measured using PDA instrument (PDA 1993) and RSM instrument are presented below. The pile was bored cast-in-place solid concrete pile with diameter 0.8 m and length of 27 m. The pile wave speed was estimated to be 3200 m/s.

Table 1 Pile Parameters and Main Test Results

Pile Parameters						F_{max} (kN)		D_{max} (mm)		WE_{max} (kN-m)		R_s (kN)	
Pile No.	D_{out} (m)	D_{in} (m)	Area (m^2)	L (m)	c (m/s)	PDA	RSM	PDA	RSM	PDA	RSM	PDA CASE	RSM CASE
100	0.5	0.3	0.125	18.5	4130	1850	1868	10.9	9.8	14.05	12.6	2200	2553
96	0.4	0.25	0.077	19.0	4130	2020	2005	10.1	9.5	12.90	12.3	2380	2725

Figure 2 shows the measured time-histories of force $F_m(t)$, and velocity multiplied by impedance, $ZV_m(t)$ using both PDA instrument (PDA, 1993) and RSM-CASE system. Figure 3 shows measured force $F_m(t)$ and computed force $F_c(t)$ using CAPWAPC (CAPWAP, 1993) and RSM-PileStar respectively. The back-computed distribution of static soil resistance on the pile surface and the pile toe and the accumulated total static resistance are shown in Fig. 4. The total accumulated resistance (computed static bearing capacity) of 5517 kN from CAPWAPC (CAPWAP, 1993) and 5346 kN from RSM-PileStar are in good agreement. However the computed resistance distribution on the pile surface and pile toe are not quite the same. Both methods show that a large resistance is due to the pile toe resistance.

The RSM instrument and PileStar software were used to measure and analyze the static bearing capacity of two piles in Hanko, Wuhan, China. Static pile loading tests were also carried to determine the static bearing capacity. The basic parameters together with the main results from the static pile tests and the back-analysis using RSM-PileStar are presented in Table 2. It can be observed from the table that the computed values are close to the values from static pile tests.

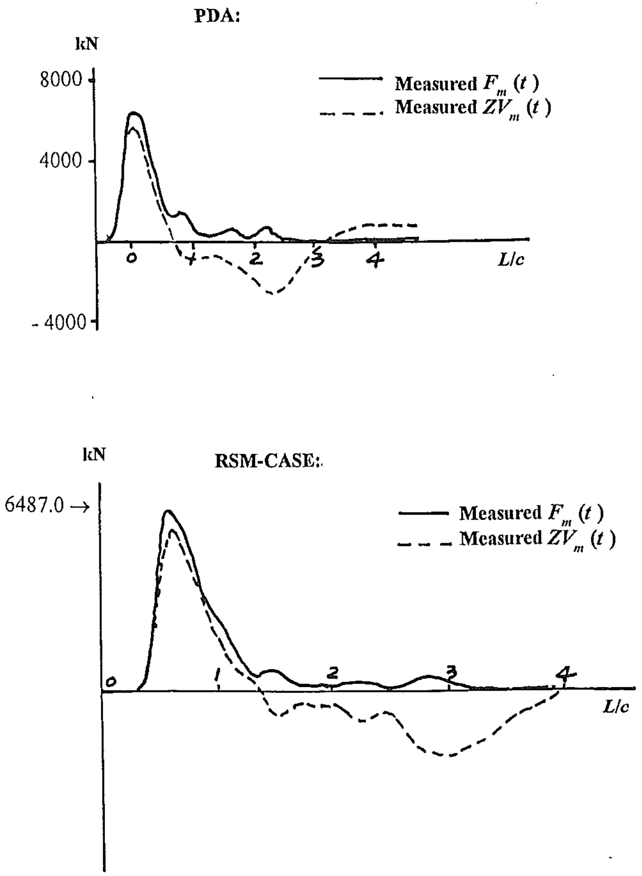

Fig. 2 Measured Time-Histories of Force $F_m(t)$, and Velocity, $ZV_m(t)$ for Pile No. 13 Using PDA Instrument (PDA, 1993) and RSM-CASE System

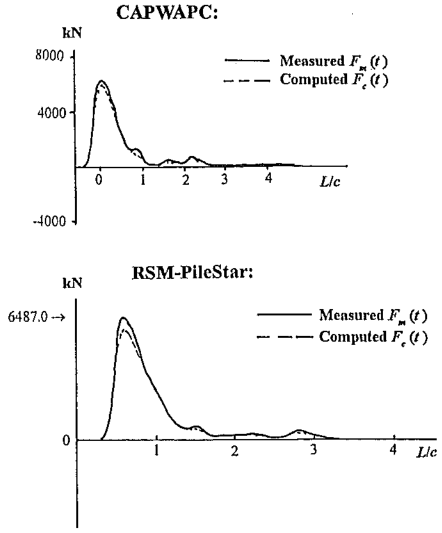

Fig. 3 Measured Force $F_m(t)$, and Computed Force $F_c(t)$ for Pile No. 13 Using CAPWAPC (CAPWAPC, 1993) and RSM-PileStar

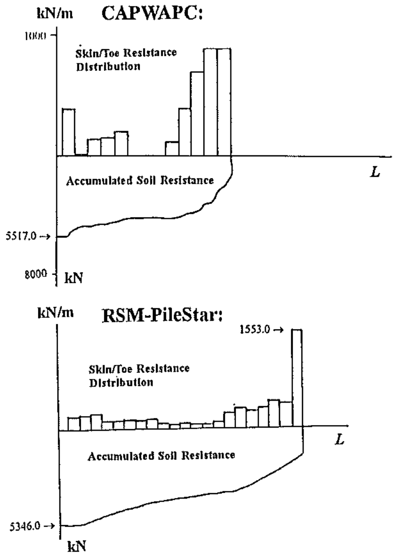

Fig. 4 Back-Computed Distribution of Static Soil Resistance for Pile No. 13 Using CAPWAPC (CAPWAPC, 1993) and RSM-PileStar

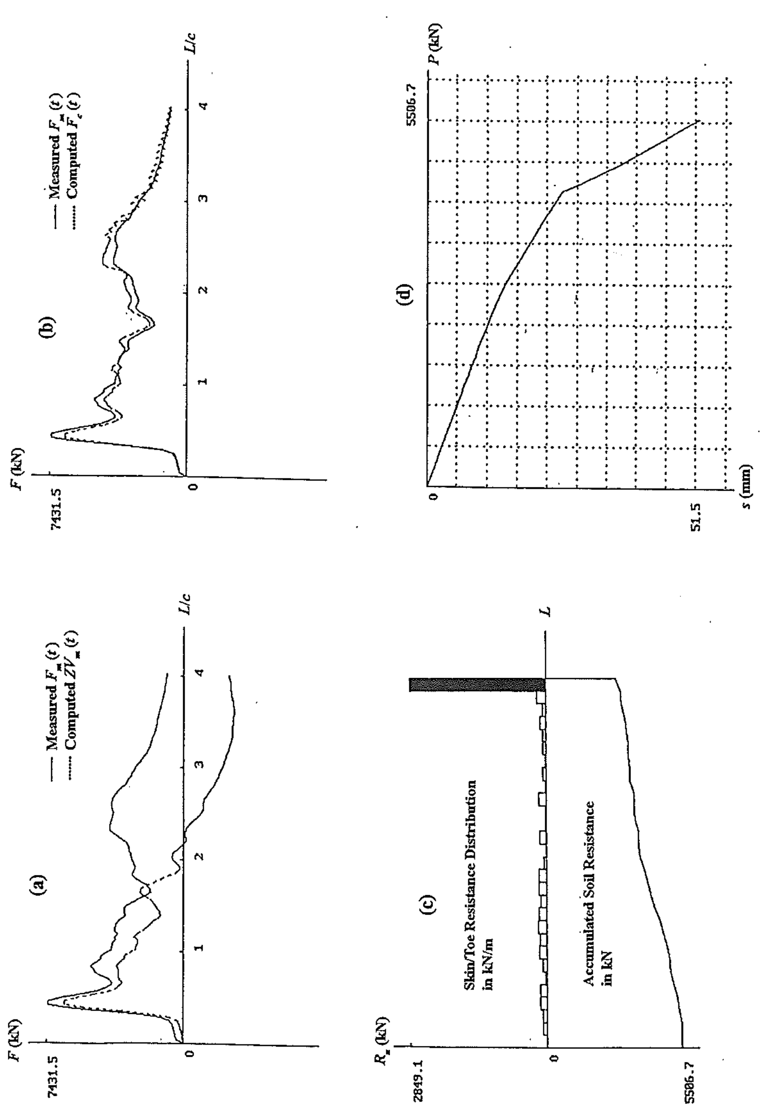

Fig. 5 (a) Measured Time-Histories of Force $F_m(t)$ and Velocity $ZV_m(t)$; (b) Measured Force $F_m(t)$ and Computed Force $F_c(t)$; (c) Back-Computed Distribution of Static Soil Resistance and Accumulated Resistance Force; and (d) Computed Static Load Versus Settlement from RSM-PileStar

Table 2 Pile Parameters and Results From Static Loading Tests and PileStar Analysis

Pile Parameters (solid pile section)							R_S (kN)	
Pile No.	Pile Type	Shape	D_{out} or B	Area (m^2)	L (m)	c (m/s)	Static Pile Tests	RSM PileStar
Hanko/195-1	Precast pile	Square	0.45	0.2	20	4600	2100	1992
Hanko/221-1	Precast pile	Square	0.45	0.2	20	4600	2500	2468

Figure 5 shows a full set of data curves from RSM-CASE and PileStar, that is, (a) the measured time-histories of $F_m(t)$ and $ZV_m(t)$, (b) measured and computed $F_m(t)$ and $F_c(t)$, (c) the back-computed distribution of static soil resistance and the accumulated total static resistance, and (d) the static load *vs.* settlement for a driven concrete pile. It is seen in Fig. 5(d) that PileStar can provide a back-calculated static load-settlement curve.

REMARKS

Bearing capacity determination using either the simple CASE method or the back-analysis method has apparent advantage in economy if used right. The two methods are based on a number of assumptions and simplifications. A good understanding on the stress wave theory is necessary. Limitations of the two methods should be recognized. Experience is required for successful applications of the methods for determining static bearing capacity of piles.

The authors consider that the following measures should be adopted in order to get more accurate determination of the pile static bearing capacity:

1. Correct set-up of the pile dynamic testing system including correct installation of transducers.
2. The hammer input energy should be big enough to mobilize pile downward displacement.
3. The empirical CASE damping coefficient J_c should be calibrated by comparing the computed capacity to the measured capacity from static loading tests at the same site for similar soil conditions and piles.
4. The back-analysis programs should also be verified by comparing the computed results to measured results from a few static loading tests at the same site and for similar soil conditions and piles.
5. Both CASE method and the back-analysis method need to assume a pile length or the wave speed. The wave speed (or pile length) may be obtained first by performing a low-strain pile integrity test. The correct input of the wave speed and/or pile length gives more reliable determination of the bearing capacity using the two methods. The high-strain dynamic pile testing cannot replace the conventional static pile testing method (Yuan, 1988a,b and GEO, 1996). If used right and calibrated, the dynamic testing can provide a fast determination or consistency checking of the pile bearing capacity.

Improvement of the back-analysis method has been and continues to be an active area of research and development. The urgent issues to be solved are (a) a refined model for the interaction between soil and pile, (b) consideration of joints and known defects in the pile in the back-analysis, and (c) improved "best" match using both automatic minimization computing procedure and manual adjustment scheme based on engineering judgment and other information about each pile and site conditions.

SUMMARY AND CONCLUSIONS

The basic equations of two wave equation methods for the pile bearing capacity determination are derived and discussed. The main original data from high-strain dynamic pile tests at three sites obtained using the instrument developed at IRSM and another instrument are presented, compared and discussed.

The CASE method and the back-analysis method may provide a fast determination (or consistency checking) of the pile static bearing capacity if used correctly. Both methods should be calibrated against static loading test results due to the assumptions and simplifications made in the two methods. Limitations of the two methods must be recognized. Further research is necessary to improve and verify the two methods.

ACKNOWLEDGMENT

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ANALYSIS OF PILE SUBJECTED TO CYCLIC LATERAL LOADING

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ABSTRACT

An analysis is proposed for studying the response of a pile embedded in homogeneous clay, subjected to cyclic lateral loading, using semi-analytical finite element approach. The pile and soil media are discretized into eight nodes of isoparametric continuum elements, while interface between soil and pile is modelled using six nodes of curved interface element. Both soil and interface were modelled using bilinear stress-strain relationships. This analysis is an extension of nonlinear static pile response, and allows for reduction of soil modulus and yield pressure with number of cycles. An iterative procedure is employed, in which a constant stiffness based on initial tangent modulus of bilinear stress-strain relationship is used in all the iterations. Effect of one-way and two-way cyclic loading on moments and deflections is studied.

INTRODUCTION

The design of offshore pile requires consideration of the effects of cyclic loading on the lateral load capacity and permanent deformation of pile head. Available methods of analysing the lateral response of piles can be broadly divided into three categories :

1. Subgrade reaction (*p-y*) analysis, modified for the effect of cyclic degradation by Georgiadis, et al. (1992) and Long and Venneste (1994);
2. Elastic continuum analysis modified for the effect of cyclic degradation by Poulos (1982); and
3. Finite element method by Kuhlemeyer (1979) and Randolph (1981).

Of the above approaches, the finite element method achieves a more rigorous solution than the other two methods, since the pile is modelled more accurately. Also, heterogeneous soil conditions are readily, and correctly, modelled.

The limited information available on the effects of cyclic loading on piles indicates that remarkable reduction in load capacity and pile-soil system stiffness can occur. In some of these cases, failure is characterized by a continued accumulation of permanent displacements resulting in movements of pile of the order of one pile diameter after several cycles of load application.

It appears that at least two mechanisms may contribute to the failure of piles under cyclic loading:

1. Cyclic degradation of soil modulus and yield stress; this may be expected to dominate under essentially two-way cyclic loading; and
2. Accumulation of permanent displacement with increasing load cycles; this may be expected to dominate under essentially one-way cyclic loading.

In this paper, an efficient iterative analysis based on semi-analytical finite element approach for the analysis of a laterally loaded pile embedded in clay subjected to cyclic loading, involving nonlinearity of soil and interface behavior is proposed. This analysis was an extension of the non-linear finite element analysis for static pile response, and allows for the reduction in soil modulus and yield pressure with increasing cyclic strain. For simplicity, the non-linear behavior of the soil was modelled using a bilinear stress-strain relationship. The nonlinearity of interface

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