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DYNAMIC PILE TESTING IN PRACTICE

ESSAIS DES PIEUX DYNAMIC EN PRACTIQUE

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SYNOPSIS: Dynamic pile testing and analysis are routine procedures in modern deep foundation practice. Measurements of strain and acceleration near the pile head under a hammer impact provide the basis for a complete analysis of the hammer-pile-soil system. Real time data analysis, according to the Case Method, yields information regarding driving system performance, pile driving stresses, structural integrity, and pile static capacity after each hammer blow. Further data analysis using the CAPWAP method determines soil resistance distribution along the pile shaft and under the pile toe. The pile head and toe load versus displacement relationship can also be obtained. This paper presents an introductory discussion of field measurement equipment and the analytical methods along with three case histories. The cases cover situations where testing was critical in determining driving system performance, pile integrity, and correlation between predicted and measured pile static capacity, pile head load-displacement, and pile-soil load transfer relationships.

1 BACKGROUND

In its most basic form, dynamic pile testing encompasses visual observations and the "measurement" of hammer stroke and pile penetration during driving. Initially, engineers "analyzed" these measurements using energy formulations based on the Newtonian physics of rigid body impact. The appeal and shortcoming of this analytical approach are rooted in its misleading simplicity and a misconception of the real nature of the problem. The applicability of the one dimensional wave equation to the pile driving problem was first suggested by St. Venant (Timoshenko and Goodier 1961). Later Isaacs (1931) and Fox (1932) presented solutions for special cases, but general purpose solutions were not easily obtained due to the complexity of the initial and boundary conditions involved.

In the 1950s, the availability of digital computers made a discrete solution of the elastic, one dimensional wave propagation problem in piles possible. Smith (1960) presented an algorithm, a computer code, and a procedure that became known as the "wave equation analysis" of pile driving. A number of sophisticated computer programs (Goble and Rausche, 1986) exist today. Wave equation is a rational analytical tool that offers means to realistically model and analyze impact pile driving. It, however, requires input parameters that, by the very nature of the problem, necessitate the employment of assumptions regarding the behavior of various elements.

2 DYNAMIC PILE TESTING

Early stress wave measurements on piles were made by Glanville et al (1938) using piezoelectric force transducers to study stress distribution in concrete piles during driving. In 1960 the Michigan Highway Commission performed research that included the measurement of force and acceleration near the pile head for evaluating driving system performance.

In 1964, a research program, funded by the Ohio Department of Transportation and the Federal Highway Administration was initiated at Case Institute of Technology (now Case Western Reserve University) in Cleveland, Ohio, USA. The purpose of the research was to develop an economical, practical, easily portable system which could calculate static pile bearing capacity from electronic measurements of pile force and acceleration during pile driving or restriking. The necessary equipment and methods were later expanded to evaluate other aspects of the pile driving process. Today, these procedures are collectively called the Case Method and are conveniently applied in the field by a device called the Pile Driving Analyzer (PDA).

Also developed during the Case research project, the CAPWAP method combines field measurements and wave equation type analysis to compute pile capacity, soil resistance distribution and dynamic behavior.

Dynamic pile testing is routinely performed for the purpose of improving pile installation and construction control methods on thousands of projects annually around the world. The following are the main objectives of dynamic pile monitoring: (a) evaluation of pile static bearing capacity, (b) determination of dynamic pile stresses during pile driving, (c) assessment of pile structural integrity, and (d) investigation of driving system performance.

2.1 Instrumentation

Dynamic measurements of pile strain and acceleration are the basis for modern dynamic pile testing. Strain transducers are reusable devices containing resistance gages attached in a full bridge arrangement. Acceleration is measured with piezoelectric or piezoresistive accelerometers. Gages are mounted on the pile shaft near the pile head with a set attached on opposite sides of the pile to monitor and minimize (by averaging) the effects of eccentric hammer impacts. The PDA is a state-of-the-art, user friendly data acquisition system and field computer that provides signal conditioning, processing, and calibration of the measured signals. Pile strains are converted to forces and accelerations to velocities as a function of time for each hammer blow. Force and velocity records are assessed by the PDA for data quality and are evaluated according to the Case Method equations. Testing results and dynamic records are permanently stored in digital form.

2.2 Case Method

Using wave propagation theory the PDA applies Case Method equations to measured records to compute some 40 variables in real time. The most interesting of these values are:

* Case Method axial pile static capacity (Rausche, et al., 1985)
* Maximum energy delivered to the pile, ram impact velocity, and cushion stiffness (Likins, 1982)
* Maximum pile compressive and tensile stresses (Hussein and Rausche, 1991)
* Pile structural integrity factor and location of damage (Rausche et al., 1988)

2.3 CAPWAP Method

The CAse Pile Wave Analysis Program (CAPWAP) is a rigorous analytical procedure that was developed to compute soil resistance forces and their distribution from measured pile head force and velocity records (Rausche, 1970). The analysis is usually performed interactively by the engineer using a micro-computer, although the program in its expert system mode can also obtain automatic solutions. The pile is represented as a continuous wave transmission model. The soil reaction is assumed to consist primarily of static (elasto-plastic) and dynamic (linear damping) components. The analysis procedure consists of signal matching pile force or velocity histories given one measurement as input and the other as a boundary condition by manipulating the soil model along the pile shaft and under its toe.

Analysis results include: static pile capacity, shaft resistance distribution, end bearing, quake, damping, pile head and toe load versus displacement relationships, and the pile-soil load transfer curve.

3 CASE STUDIES

The following are three case studies illustrating the effectiveness of dynamic pile testing in evaluating hammer performance, pile structural integrity, and pile static capacity and distribution. A brief theoretical discussion prefaces each subject. Physical field verifications, by pile extraction or static loading tests, were performed in each case.

3.1 Hammer Performance Evaluation

To a contractor, a pile driving hammer is a mass production machine, and to an engineer, it is an instrument that is used to measure the quality of the end product. If the sole function of a hammer is to drive piles into the ground, then its efficiency is not important to the engineer. However, implicit assumptions regarding hammer performance are the basis of common pile design and analysis procedures. Hammers are normally rated according to their potential energy (WH), but it is only the energy reaching the pile that is of any use in causing pile penetration. Energy losses due to mechanical friction, cushion compression, and general dynamic incompatibility are often more than half the available potential energy.

Given records of force and velocity, the PDA calculates the transferred energy as:

$$E(t') = \int_0^{t'} F(t)v(t)dt$$

where F(t) is the force and v(t) is the velocity in the pile, both measured as functions of time. The maximum of the E(t') curve, printed by the PDA as EMX, is the most important information for an overall evaluation of the driving system performance. The transfer efficiency, defined as the ratio of EMX over rated hammer energy, is an index to evaluate the efficiency of pile driving. The following example shows the importance of this information in piling practice.

3.1.1 Case 1

A Raymond single acting air hammer (rated energy of 85 kJ) was proposed to drive cylindrical post-tensioned concrete piles (1.37 m outside diameter and 127 mm wall thickness). The hammer cushion consisted of layers of aluminum and micarta with a combined thickness of 580 mm. Sheets of plywood with a thickness of 152 mm were proposed as the pile head cushion. The pile, with a length of 24.4 m, was to be driven 10.4 m through soft silts and clays into dense silty sand. A standard wave equation analysis was performed to obtain a bearing graph relating pile driving blow count to static capacity and stresses. The normally assumed hammer efficiency of 67% was used along with other required modeling parameters. In the field, the pile was driven to a blow count of 197 blows for 0.3 m of penetration. Wave equation analysis showed that at this blow count, the pile's capacity is 6340 kN, the maximum compressive stress 13 MPa, and the pile head transferred energy 28.6 kJ. As part of construction control monitoring, a PDA was employed during pile installation. Field dynamic testing showed significantly different results than those of the analysis predictions. The actual transferred energy was 10.9 kJ, the maximum compressive stress 6.9 MPa, and the pile dynamically predicted static capacity 2850 kN. This energy transfer translates to a transfer efficiency of 12%.

Statistical studies performed by the authors' organization on a large number of projects where concrete piles were installed by air hammers found the transferred efficiency to average approximately 40%. A static loading test performed on the pile indicated a failure load of 3000 kN. After the fact, a new wave equation analysis was performed after modifying the hammer efficiency (down to 23%) to reflect actual field performance. Figure 1 presents plotted results of both wave equation analyses. The modified analysis indicated that at a blow count of 197 blows for 0.3 m, the maximum transferred hammer energy was 10.9 kJ, the pile compressive stress 6.5 MPa, and the pile static capacity 2760 kN.

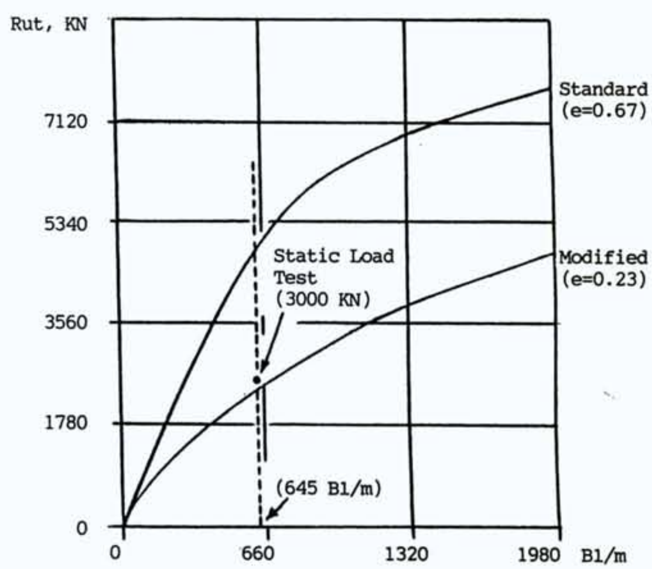

Fig. 1. Bearing Graph from Wave Equation analysis of Case 1

3.2 Pile Structural Integrity

Under the impact of a hammer, piles are subjected to a complex combination of forces. Pile damage occurs when driving stresses exceed pile material strength. Piles may be damaged at their heads, toes, and/or along their shafts.

Stress waves in a pile are reflected whenever the impedance changes. The reflected waves arrive at the pile head at a time which depends on the location of damage. The reflected waves cause changes in both pile top force and velocity records. The magnitude of relative change of the pile top variables allows for determination of the extent of impedance change. Thus, with β being a relative integrity factor which is unity for no impedance change and zero for a pile end, the following can be calculated by the PDA,

$$\beta=(1-\alpha)/(1+\alpha)$$

with

$$\alpha=1/2[(W_{ur}-W_{ud})/(W_{di}-W_{ur})]$$

where W_{ur} is the upward traveling wave caused by soil resistance at the onset of the reflected wave, W_{ud} is he upward traveling wave due to the damage, and W_{di} is the maximum downward traveling wave due to impact.

The following example illustrates the use of dynamic testing in detecting and evaluating pile damage.

3.2.1 Case 2

The piles on the job were 457 mm square prestressed concrete sections with a total length of 51.8 m consisting of two sections (36.6 and 15.2 m) spliced in place. Pile driving was accomplished with a DELMAG D46-32 open end diesel hammer. Dynamic testing was performed during pile driving after the addition of the second pile section. Figure 2 presents plots of pile head force and velocity records representing four hammer blows from the beginning, middle, and end of testing. During installation, maximum pile compressive

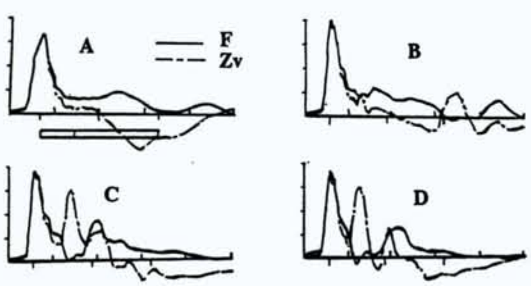

Fig. 2. Measurements obtained on the Case 2 pile during the develop ment of damage

Fig. 3. Case 2, Damaged pile after extraction

and tensile stresses reached 30 and 6.2 MPa, respectively. Figure 2a shows a pile that has a continuous shaft (β=100), Figure 2b includes reflections that indicate "slight" pile damage (β=85) at the splice location, Figure 2c presents records of a "broken" pile (β=36) at the splice, and Figure 2d also indicates pile breakage, but at a second location approximately 1.5 m above the first damage location.

Pile damage (particularly the first damage) was not apparent to field inspection personnel and was only detected by the PDA dynamic records. For verification, the pile was extracted and damage was confirmed as shown in Figure 3.

3.3 Pile Static Capacity and Soil Resistance

Given records of pile force and velocity and assuming an ideally elastic and uniform pile, it can be shown that the total soil resistance force may be computed (Rausche et al., 1985). This total resistance is thought to consist of a dynamic and a static component. The static resistance component is the desired pile bearing capacity and it is determined by reducing the total resistance using a damping factor, J. The damping factor is assumed dependent on soil grain size. This solution is simple enough to be evaluated in real time using the PDA. The static capacity value computed is that at the time of testing. Dynamic monitoring during restrike provides information regarding time dependent pile capacity changes.

Data analysis with CAPWAP yields further information on soil resistance and behavior.

3.3.1 Case 3

A pile driving and load test program was undertaken to assess pile drivability and bearing capacity and determine foundation design parameters. The pile discussed here is one of eight test piles involved. This 305 mm square, 27.7 m long prestressed concrete pile was driven with an ICE 640 diesel hammer into calcareous clayey sand. Dynamic pile testing was performed during initial driving and also during restrike 22 days later. The pile was instrumented with ten embedment-type, vibrating wire strain gages to measure load transfer to the pile during the static load test which was performed 21 days after pile installation.

Computed total driving resistance was 2400 kN; with a Case Damping factor J=0.6, the resulting static pile capacity was 1629 kN. Figure 4 presents static loading test results and it indicates a Davissons failure load of 1600 kN. Also included in Figure 4 is the CAPWAP

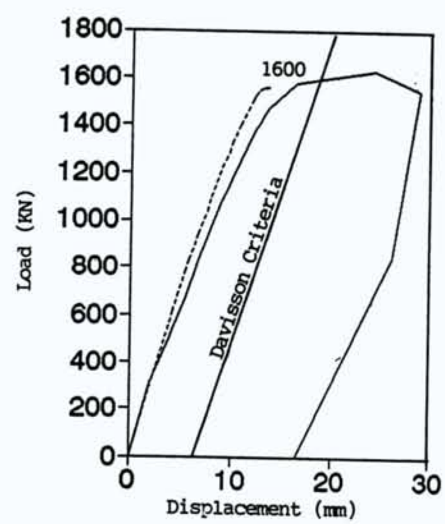

Fig. 4. Comparison between the measured and CAPWAP simulated load test curve

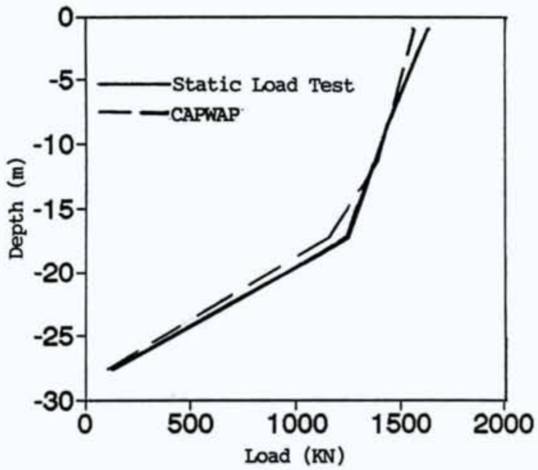

Fig. 5. Force in the pile measured statically and by CAPWAP from dynamic measurements

simulated pile head load-displacement graph. Pile forces at ultimate load as a function of depth are presented in Figure 5 from both static and dynamic tests. For this pile, static capacity computed by the Case Method and CAPWAP were within 1.8 and 2.8%, respectively, of that determined from a full scale static loading test. The CAPWAP method also closely predicted soil resistance distribution and the pile head load-displacement relationship.

4 CONCLUSIONS

Three examples have been presented to illustrate the usefulness of dynamic pile monitoring in the design and construction control of pile driving. In the first case poor hammer performance would have given a large over-prediction of the pile capacity if measurements had not been available. In the second case pile damage was very clearly indicated. The last case was an example of the use of field measurements to establish the driving the driving criteria prior to design. In all cases the field measurements provided useful results.

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