DETERMINATION OF DRIVING INDUCED PILE DAMAGE
DÉTERMINATION DU DOMMAGE DES PIEUX LORS DU BATTAGE

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During installation, driven piles are subjected to compressive, tensile, bending, and torsional stresses; these stresses are perhaps the highest the piles will ever experience during their service lives. Furthermore, piles are not made perfect and therefore may be damaged during driving. Frequently, engineers require dynamic pile testing by the Case Method to evaluate the performance of the hammer-cushion-pile-soil system during pile driving. Using a Pile Driving Analyzer (PDA), these methods provide information regarding pile driving stresses and structural integrity after each hammer blow in real time during installation. This integrity assessment by the so called "high strain" method includes equations for determining location and extent of pile damage.

This paper presents four case histories where dynamic measurements were used to identify pile damage. In three cases, the piles were extracted, or exposed and damage was verified. The case studies cover uniform and non-uniform piles with and without splices, concrete and steel pile materials, homogeneous and layered soil conditions. Information regarding pile driving stresses, blow counts, and subsurface profiles are presented in each case. In some cases the dynamic measurements indicated pile damage well before it became apparent from the pile driving behavior. In other cases, it was not noticeable from behavior that the pile had broken.

Pendant l'installation, les pieux battus sont soumis à des contraintes de compression, tension, flexion, et torsion. Ces contraintes sont peut-être les plus élevées auxquelles les pieux seront soumis pendant leurs durées de vie. En outre, les pieux n'étant pas fabriqués en état parfait, ils pourraient être endommagés lors du battage. Souvent les ingénieurs ont besoin d'essais de chargement dynamique, utilisant la "CASE METHOD", pour évaluer le comportement du système marteau-coussins-pieu-sol, pendant les opérations de battage. Utilisant le "PILE DRIVING ANALYZER", cette méthode donne des informations sur les contraintes engendrées par le battage, ainsi que l'état structural des pieux après chaque coup de marteau, pendant l'installation. L'évaluation de l'intégrité des pieux par la méthode des "Déformation Elevees" (High Strain) comporte des procédures pour déterminer l'emplacement et l'étendue des défauts et dégâts des pieux.

Quatre cas historiques sont presentés où des mesures dynamiques ont montré des pieux endommagés. Dans trois cas, les pieux ont été arrachés ou exposés pour vérifier les dommages. On rend compte des cas de pieux à section uniforme et non-uniforme, des pieux métalliques ou en béton, ancrés dans des sols homogènes ou multi-couches. Pour chaque cas etudié, les contraintes engendrées et les conditions du sol sont présentées. Dans certains cas, les mesures dynamiques ont bien indiqué du dommage avant qu'il devienne évident par le comportement des pieux lors du battage. Dans d'autres cas, les essais dynamiques ont permis de déceler des pieux cassés bienqu'aucun comportement anormal n' ait été observé lors du battage.

INTRODUCTION

Pile driving is a brutal procedure of foundation construction. While the installation process itself constitutes a "test" for the soundness of the pile in-place, it can also be the cause of pile structural failure. Damage to piles during driving has been noted with considerable frustration since antiquity . All driven pile types (*i.e.*, timber, concrete, steel, and composite) under various conditions (*i.e.*, friction, end bearing, or a combination of both) are subject to structural failure during installation. Observations like driving resistance, made during installation, have long been used to evaluate the structural integrity (or the lack of it) of driven piles; they can, however, be misleading.

During driving, piles are subjected to compressive, tensile, flexural, and torsional forces. Overstressing the pile material results in damage; fatigue may result in pile damage at lower stress levels. Common modes of pile damage include: yielding or crushing at the pile head, toe or shaft, cracking (vertical and horizontal) of concrete pile shaft, "slabbing" (the loss of the concrete covering reinforcement) at concrete pile head, and failure of splices. Causes of driving induced pile damage include: inappropriate hammer; insufficient cushioning; tight pile cap; misalignment between pile and driving system; very easy, very hard, or "bouncy" driving conditions (when soil has a great flexibility and large rebound displacement occur); obstructions in the ground; uneven contact between hammer and pile head, or pile toe and concentrated soil resistance; and/or lack of lateral pile support. Furthermore, piles are not made perfect (geometry and material), and they may have experienced excessive stresses and therefore cracking during both transportation and placement under the hammer which will be the root of greater damage during driving.

Frequently, engineers require dynamic pile testing by the Case Method to evaluate the performance of the hammer-cushion-pile-soil system during pile driving. Measurements of force and velocity of the pile under a hammer blow are processed by the Pile Driving Analyzer (PDA) that applies Case Method equations to compute: pile driving resistance and static capacity, hammer/cushion performance, pile driving stresses, and an evaluation of pile structural capacity (1). This integrity assessment by the so-called "high strain" method includes routines for determining location and extent of pile damage in real time after each hammer blow (2). Other methods using "low strain" impacts generated by small hand held hammers are also available for pile structural integrity evaluations (3) after driving is completed.

This paper presents the basics of wave mechanics and the development of dynamic pile driving stresses in a pile during a hammer blow. It describes dynamic pile testing and the Case Method equations for calculated pile stresses and the integrity factor β, along with four case histories where pile damage was detected.

WAVE MECHANICS

When a hammer strikes the pile head, the suddenly applied compression force travels along the pile in a wave form at a constant speed, c, which is a function of the material elastic modulus and density. For a uniform pile with no soil resistance, the intensity and length of the stress wave is a function of: (a) hammer ram weight, (b) ram impact velocity, (c) stiffness of the cushions under hammer and between helmet and pile top, (d) pile cap weight, and (e) pile weight and stiffness. The compressive wave reaches the pile toe at a time L/c after impact (where L is pile length) and reflects as an upwards traveling tension force. If a shaft friction or an end bearing force is generated by the pile motion, then a compressive wave will also travel upwards and reduce the effect of the tension wave. If the compressive stresses induced by impact exceed the material strength, then pile crushing will occur at the pile top. If the soil resistance is low and the reflected tension is high, then pile shaft will crack. For purely end bearing piles with high resistance, the compressive force at the pile toe could possibly double in magnitude. This can cause pile toe damage even though the initial compressive stress was not sufficiently high to cause the more obvious pile top damage. In cases where the pile length is long compared to the impact induced stress wave length, the compressive forces generated by high resistance may reach the then free pile top (after ram rebound) and reflect again as a tension force traveling down the pile shaft. A situation of high tension may also occur in hard driving. If the soil resistance has a great flexibility (*i.e.*, bouncy driving), then the soil response builds up too slowly to cancel the early tensile reflections.

Soil resistance distributed along the pile shaft generates upwards traveling compressive force waves. They add to the impact induced compressive pie forces. If the soil resistance is of high enough magnitude and concentrated close to the pile top, then the superposition of the impact and reflected compressive forces may generate stresses that exceed the pile strength. Another cause of wave reflections is change in pile impedance $Z(Z = EA/c$; where E is elastic modulus and A is cross sectional area). An increase in impedance causes a compressive reflection and a decrease causes a tension wave. For severe and abrupt impedance changes, these reflections may add enough to the input generated forces to cause pile damage.

In addition to axial forces, piles are subjected to bending stresses either caused by eccentric impacts, non-uniform soil resistance at pile toe, or by forcing the pile in a certain direction with the leader. Not as frequently observed are torsional stresses caused by a twisting motion of the pie in the soil and a binding of the pile top in a tight cap. In many cases, piles are subjected to a complex combination of most of the above mentioned forces.

Rational analytical procedures (*i.e.*, Wave Equation Programs (4)) incorporating personal computers are available to study the compatibility of the hammer-cushions-pile-soil system and to assess the drivability of the pile in order to insure safe and economical pile installation. Electronic equipment and methods are also available to monitor pile installation and to either measure or compute either axial or bending pile stresses during driving and to assess pile structural integrity.

CASE METHOD

In 1964 research was initiated at Case Western Reserve University in Cleveland, Ohio aimed at the development of methods to compute static pile capacity given field dynamic measurements of pile force and velocity under a hammer blow. The research was successful and the procedure became known as the "Case Method". The method was later expanded to evaluate hammer performance, pile driving stresses (compressive and tensile), and pile structural integrity assessment from the same dynamic pile top force and velocity records. In general, a Pile Driving Analyzer (PDA) is used to (a) condition the necessary signals and (b) to calculate the Case Method results between hammer blows.

The basis of pile monitoring is the measurement by the PDA of pile top force and velocity caused by the impact of a hammer blow. The signals are obtained using two piezoelectric accelerometers and two bolt-on strain transducers attached to the pile approximately two diameters below its top. One each of the gages are bolted at opposite sides of the pile. The PDA conditions and calibrates these signals and computes average pile force and velocity, then applies Case Method solutions to the data. Required PDA inputs include pile length, area, elastic modulus, and wave speed, in addition to specific gage calibration factors.

An applied hammer impact causes at the pile top a force (F) and particle velocity (v). As long as the wave travels in one direction and no reflections are introduced, it can be shown that the force, F, and velocity, v, are proportional:

$$F = vZ \tag{1}$$

Soil resistance forces (R) or an increase in pile impedance cause a relative increase in force and a relative decrease in velocity at the pile top. A decrease in pile impedance will produce an opposite effect. Since both force and velocity are measured, the forces in the upward, Wu, and downward, Wd, traveling waves can be computed from:

$$W_d = (F + Zv)/2 \tag{2a}$$

$$W_u = (F - Zv)/2, \tag{2b}$$

respectively. Typical measured pile top force and proportional velocity records along with corresponding wave up and wave down traces are shown in Figure 1. Using Equation 2(a) and 2(b), it can also be shown that the total soil resistance is

$$R = [(F(t_1) + F(t_1+2L/c) + Zv(t_1) - Zv(t_1+2L/c) \tag{3}$$

where time (t_1) is normally taken at the first major velocity peak.

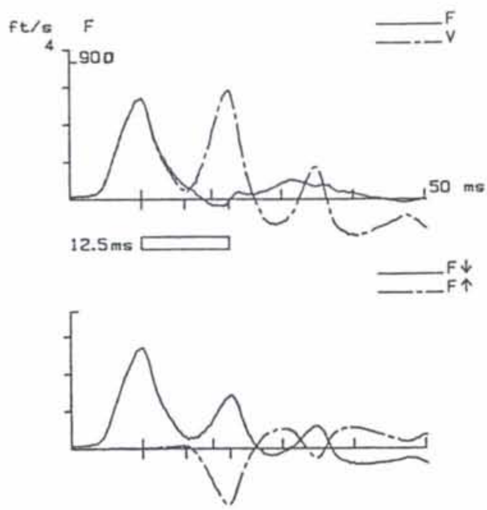

Figure 1: Sample Pile Top Dynamic Records

Pile top compressive stress can be directly obtained from the measured data as the maximum magnitude of the measured force record. Since strain gages are attached at opposite sides of the pile, monitoring each one separately allows the detection of any non-axial force components. For concentrated end bearing, the compressive force at the pile toe can be calculated from pile top measurements and one dimensional wave propagation considerations. Maximum dynamic tension forces occur at some point below the pile top. Again, the maximum tension force can be computed from the pile top measurements by considering the magnitude of both upward and downward traveling waves. If any one of these waves is negative, a tension wave exists. It is also checked whether the wave traveling in the opposite direction is sufficiently compressive to reduce the net tension force.

It has been pointed out that stress waves are reflected wherever the pile impedance (Z) changes. The reflected waves arrive at the pile top at a time which depends on the location of the change. (If a change occurs at a distance "x" below pile top, then its effects on the pile top records will be evident at a time t=2x/c after impact). The reflected waves cause changes in both pile top force and velocity. The magnitude relative change of the pile top variables allows to determine the extent of the impedance change. Thus, with "β" being a relative integrity factor which is unity for no impedance change and zero for the pile end, the following can be calculated:

$$\beta = (1-\alpha)/(1+\alpha), \text{ with} \tag{4a}$$

$$\alpha = [(W_{ur}-W_{ud})/(W_{di}-W_{ur})]/2 \tag{4b}$$

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

Using the measured pile top records, the PDA automatically computes all of the above mentioned stresses and damage location and extent in real time for each hammer blow. The following examples illustrate the use of dynamic measurements in determining pile driving stresses and structural damage. Since these are all case histories with the original work done in the English units, the same unit system will be followed here. A conversion table between English and SI units is included in Appendix A.

CASE 1

A pre-construction pile load test program was undertaken for a 14 story hotel project. The program included the driving and monitoring of nine piles (four prestressed concrete and five closed ended steel pipes). This case history will consider one of the steel piles that failed structurally during driving.

Generally, the soil conditions consisted of silty sand with clayey layers. A relatively hard layer existed at a shallow elevation. Thus, a 12-inch bit auger with a water jet was employed to form a hole 30 ft in depth. The bearing layer consisted of dense sand, however, the depth at which it could be found varied greatly across the site. At the location of the subject pile, the dense sand layer was thought to be at a depth of 150 ft below ground level. The pile had an outside diameter of 12.75" with 0.375" wall thickness (area of 14.6 in2), and had a total length of 135 ft consisting of two 67.5 ft sections. The top piece was welded to the already driven bottom section. Pile driving was accomplished using a Vulcan 80C double acting air hammer (rated energy of 24.45 kip-ft). Sheets of Aluminum/micarta were used as hammer cushions. The pile was driven to a depth of 130 ft. During its installation, the driving resistance was one blow per foot (BPF) at a depth of 30 ft and increased by 1 BPF for each 15 ft of penetration, ending at 7 BPF at the end of driving. Case Method computation using pile top measurements indicated that pile top compressive stresses were approximately 20 ksi (material yield strength reported to be 36 ksi), pile toe compressive stresses were negligible, and pile tension stresses did not exceed 12 ksi and generally occurred at a distance of 20% of pile length below the pile top. During the last foot of driving, dynamic measurements indicated that the pile was failing at the splice Eventually, the two pile segments separated. Pile top records of force and proportional velocity representing the last four blows of driving are presented in Figure 2. They clearly show the effect of the splice (top figure) observed throughout the driving and its eventual failure during the last blow (bottom traces). Field observations during pile installation, including

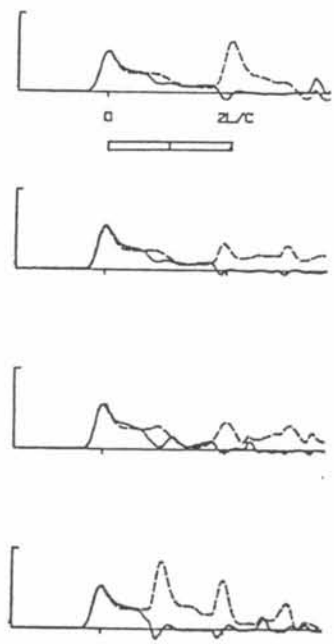

Figure 2: Dynamic Pile Top Records, Case 1

driving behavior, did not indicate the structural pile failure. Using the crane line, the top section of the pile was pulled out of the ground with ease.

CASE 2

Deep foundations for a 4-mile long bridge were constructed of precast prestressed concrete piles varying in length between 50 and 150 ft. This case study involves one of the piles on the job. Water depth at the pile location was 15 ft and the soils consisted of clayey sand to a depth of 70 ft under which limestone was encountered. The pile was a 30 inch square (area of 900 in^2) prestressed concrete with a circular void reducing the area to 646 in^2 starting 6 ft below pile top and ending 4 ft above its bottom. The total pile length was 90 ft, and dynamic measurements gages were bolted to the pile 3 ft below its top. A Conmaco 300E5 single acting air hammer operating with short stroke (rated energy of 50 kip-ft) drove the pile to a depth of 62 ft and a resistance of 128 BPF. The hammer stroke was then doubled and the pile was driven an additional four feet with a driving resistance of 7,7,10,9,9,16,12,9,6, and 4 per 0.1 ft for the last foot of penetration. After operating the hammer with the longer stroke, pile top compressive stresses averaged 1.6 ksi while tension stresses were negligible. Due to pile nonuniformity, calculations of pile toe force were not possible, but were indicated to be approximately equal to those at the top. Reflections at points of pile area may, however, cause stresses to be higher at these locations.

Pile top dynamic measurements indicated pile damage during the last foot of driving, but this was ignored by the pile driver. During the last few blows, pile damage approximately 5 to 10 ft above the pile toe was evident in the records. Figure 3 shows pile top records of force, proportional velocity, wave up, and wave down during the first and last blows of high stroke driving. The pile was extracted using water jets and pile damage was verified (Figure 4).

CASE 3

New loading docks were needed as part of the expansion of a major seaport. Most of the new construction was founded on 18 inch square (area of 324 in^2) prestressed concrete piles. Dynamic pile measurements were periodically required to be performed during production for general construction control and pile static capacity verification. Soil conditions were uniform consisting of a clayey silty sand layer to a depth of 50 ft under which soft limestone existed. During one of the routine testing visits to the job, a pile was damaged during installation. The pile was 67 ft long, driven with a Delmag D36-32 open ended diesel hammer. The pile was driven to its full length at a constant driving resistance averaging 7 blows per inch for the last 4 ft of penetration. During the entire pile driving operation, pile top compressive stresses averaged 2.2 ksi, pile toe stresses were lower, and tension stresses did not exceed 0.8 ksi. At a depth of approximately 63 ft, dynamic records indicated slight pile damage at a location approximately 56 ft below pile top. The extent of damage progressively increased with continued driving. Figure 5 presents pile top records from the last installation hammer blow. Since visual field observations did not give any reasons for suspicion, driving was continued. The location of damage coincided with that of the lifting point. The pile was not extracted, but was incorporated into the foundation with a lower bearing capacity capability.

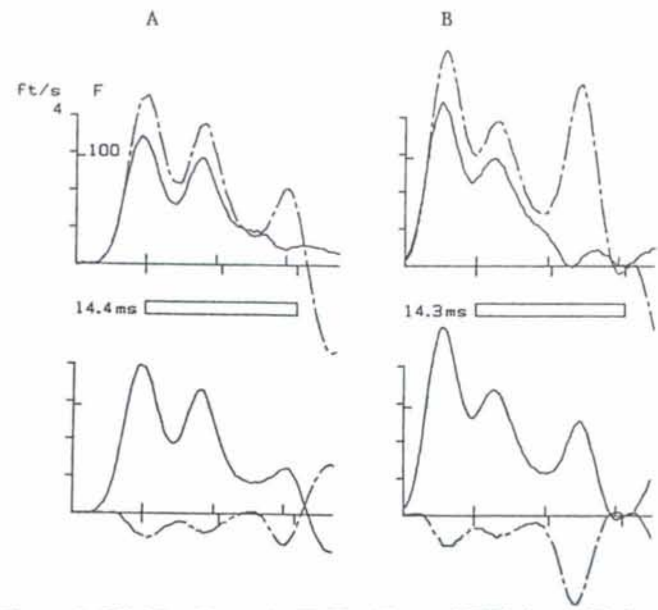

Figure 3: Pile Top Records (F, Zv, Wu, and Wd) for an Early and Last Blows, Case 2

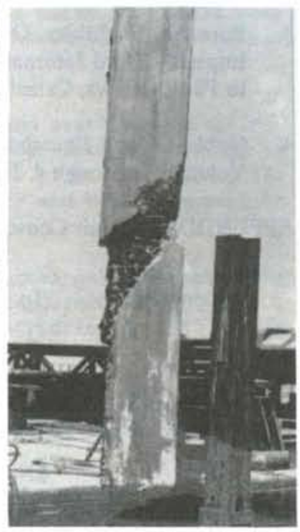
Figure 4: Pile Bottom Section after Extraction, Case 2

CASE 4

Construction of a new wastewater treatment plant required a piled foundation. The piles were 12 inch square (area of 144 in^2) prestressed concrete with an average length of 55 ft. A Link-Belt 520 double acting diesel hammer (5000 lb ram weight and 30 kip-ft rated energy) was used to install the piles. Subsurface conditions consisted of alternating clay and sand layers with hard clay lenses at some locations. Pile compressive and tensile stresses did not exceed 2.6 and 0.5 ksi, respectively; and driving resistance varied between 10 and 35 blows per foot consistent with corresponding soil layers. At a depth of 30 ft, dynamic measurements indicated pile damage at a location 38 ft below pile top, and later, at a second location, 16 ft below pile top. Alternating blow counts were explained by others to reflect the local soil conditions. Driving stresses were of low enough magnitude as not to cause pile damage. The pile was exposed and the damage closer to the pile top was verified. The reasons for the damage were not apparent. On the day after the test, however, it rained and cracks in the piles stacked up at the site became apparent. Eight of the 15 piles tested showed signs of structural damage. Evidently, pile cracking happened during pile transportation from the hauling trucks to the pile driving location. A backhoe was used to "drag" the pile across the site. The handling cracks developed into damage during driving.

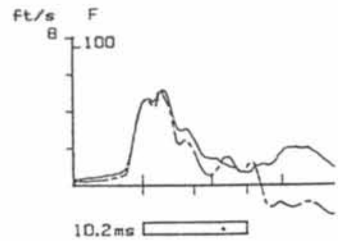

Figure 5: Pile Top Records Indicating Early Wave Reflections, Case 3

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APPENDIX A - Unit Conversion Factors

To Convert	To	Multiply By
ft	m	0.3048
in	cm	2.54
lb	N	4.45
kip	kN	4.45
psi	kPa	6.89
ksi	MPa	6.89
kip-ft	kJ	1.36