DRIVING LONG PRECAST CONCRETE PILES

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ABSTRACT: Increasingly, piles of greater lengths are required to support structures over difficult subsurface conditions. Driven precast concrete piles are often considered and have distinctive characteristics that make them well suited as deep foundation elements. This paper discusses various considerations when using concrete piles and illustrates their successful use in three case histories where prestressed concrete piles over 100 ft (30 m) in length were successfully driven. In each case, the piles were tested dynamically which provided analysis of pile driving stresses, structural integrity, and bearing capacity after each hammer blow.

1. INTRODUCTION

Deep foundations are considered when structural loads need to be transmitted through weak soils to deeper more competent strata, to resist uplift or lateral loads, to support structures over water, or provide protection against scour. Piles may be made of wood, steel, concrete, or a combination of these materials.

Wood piles with lengths up to 60 ft (18 m) normally support light loads and have comparatively lower cost. Disadvantages include low strength limits and special protection required when piles extend above the ground water table. The most common steel piles are pipes (both open and closed bottoms), H-sections, and fluted tubes (Monotubes). Steel pile advantages are strength, light weight, and the relative ease of handling, splicing and cutting to required lengths. Disadvantages include small cross sectional area and susceptibility to corrosion. Closed end steel pipes are normally filled with concrete after driving to increase their stiffness and serviceability.

Concrete piles are either cast-in-place or precast. Cast-in-place piles are constructed by drilling holes and filling them with concrete. This type of piling has relatively low cost, ease of length variation, and minimal ground vibrations during installation. A major disadvantage is the uncertainty of the shape and condition (*i.e.*, integrity) of the constructed pile. Steel casings (temporary or permanent) and/or reinforcing cages may also be required. Cast-in-place concrete pile lengths are limited by the drilling equipment used.

With the exception of cast-in-place concrete piles, most piles are installed with impact pile driving hammers powered by steam, compressed air, diesel, or hydraulic fluid. With modern electronic field instrumentation producing expanded knowledge of pile and soil behavior under hammer impacts, pile driving analysis has been vastly improved, thus making it possible to engineer a previously empirical process. This paper reviews the design, installation, testing, and construction control procedures of long precast concrete piles.

2. PRECAST CONCRETE PILES

Precast concrete piles are usually constructed in a casting yard and transported to the job site. They are either regularly reinforced or prestressed to resist handling and driving stresses. Both types come in a variety of cross sections (e.g., square, cylindrical, octagonal, etc.). Precast concrete piles may be manufactured full length, or in sections which can be spliced during installation. These piles are suitable as friction piles when driven in sand or clay, or as end bearing piles when driven through soft material to firm strata. Regularly reinforced concrete piles generally develop cracks during handling, transportation, and/or installation which has limited their general use in the U.S.A. (although they are used extensively in Europe).

2.1 Prestressed Concrete Piles

The primary advantages of prestressed concrete piles are added tensile strength and durability. Prestressing allows longer piles to be safely handled and installed and prolongs the pile's service life, since any hairline cracks are tightly closed. These piles can be either pretensioned or post-tensioned. Pretensioned piles (also commonly referred to as prestressed piles) are formed in very long permanent casting beds with dividers to produce individual piles. High strength steel strands are generally used for prestressing; however, using fiberglass strands appears promising (Sen et al., 1991).

Most common concrete piles in the U.S.A. are prestressed, mostly solid square between 10 and 30 inch (250 to 750 mm) in cross section. Frequently, larger sizes with longer lengths are cast with a hollow core to reduce pile weight and facilitate handling. Where piles are expected to drive through hard layers or to rock, pile toes may be reinforced. In some cases, a steel H-section up to 15 ft (5 m) in length is cast to the pile bottom.

Several special systems have been used for splicing prestressed concrete piles during installation (Fuller, 1983). Splicing can be accomplished by installing dowel bars and then injecting grout or epoxy. Oversize grouted sleeves are also used. To avoid these "bonding" processes, several systems have been used including welding of plates or pipes cast at the pile ends. Some systems use mechanical jointing techniques using pins to reduce the time required to make a splice. The above methods all transfer some tension through the splice. However, since the prestress requires a development length, the ends of a prestress pile must still be reinforced with dowels or regular reinforcing to transfer the tension forces through the splice area. There are also systems usually involving external sleeves (or "cans") which do not transfer tension forces, an advantage for longer piles when tension stresses would be high but not applicable to piles subject to uplift loading. Special machines are also available for pile cutting including saws and hydraulic crushing systems.

Post-tensioned piles are mostly cylindrical typically up to 66 inch (1680 mm) and are centrifugally cast in 16 ft (5 m) long sections and assembled to form the required length before driving. Prestressing is achieved by placing tensioned steel cables through ducts cast in the cured sections laid end to end. Piles up to 200 ft (60 m) have been assembled and driven.

Prestressed concrete piles carry high loads (both axially and laterally) and can be used as structural columns above ground level. They are generally considered non-corrosive, particularly when special cements, additives, and/or coatings are used. Pile structural design and handling procedures are guided by standards issued by ACI (1980), PCI (1977) and other organizations. Concrete piles usually have a strength in excess of 5000 psi (700 kPa) and a net prestress of about 1000 psi (150 kPa). Handling may be done using one pickup crane line, although longer pile lengths may require two or more pickup points.

2.2 Driving Prestressed Concrete Piles

Concrete piles are generally installed with impact pile driving hammers. Pile tops are always protected during driving with cushioning material, usually sheets of plywood. The hammer impact suddenly applies a compressive force "wave" which travels down the pile shaft at a constant speed, c, which is a function of material elastic modulus E and density ρ ($c^2 = E/\rho$). Wave speeds for concrete range between 10,000 and 15,000 ft/s (3,000 to 4,600 m/s). For a uniform pile, the magnitude and duration of the input compressive stress wave is a function of hammer ram weight and drop height, stiffness of the cushions, and pile modulus and area. For a pile with little resistance, the compressive wave reaches the pile toe and reflects as an upward traveling tension force. Tension stresses often are the controlling factor for long concrete piles. Increasing the prestress reduces the net tension, but also reduces the maximum allowable compression stress. Other common tension stress control methods reduce the input compression stress by decreasing the ram drop height or fuel setting or increasing the pile top cushion thickness. If the compressive stress caused by the impact, or the tension stress caused by the wave reflection exceeds pile material strengths, then pile damage can occur. Soil resistance (particularly along pile shaft but also under pile toe) reduces the tension during driving.

For piles with high end bearing, the downward compression also reflects in compression; thus potentially doubling the compressive stress at the pile toe even though the initial pile top compressive stress was modest. In cases where the pile length is long, the upward traveling compressive stress wave generated by high soil resistance may then reflect at the pile top as a downward traveling tension wave. Another cause of wave reflections is change in pile impedance Z (=EA/c, where A is the pile area). A decrease in impedance, crack and/or gap at a splice causes a tension reflection.

In addition to axial forces, impact driven piles experience bending stresses (caused by eccentric impacts, non-uniform pile cushion, or non-square pile top) and torsional stresses. Concrete cylinder piles are also subject to potentially serious Poisson effects (Bailey and Sweeney, 1988). The hoop stress (proportional to compressive stress by Poisson's ratio) is limited by the pitch and size of the spiral reinforcement. This effect can cause vertical cracks which limits the allowable compression stress. Square piles with center voids are subject to the same phenomena but the non-rotationally symmetric shape defines the location of the vertical cracks. During driving, piles experience a combination of the above mentioned forces. The structural pile strength must be sufficient and the installation procedure properly controlled to prevent overstressing the pile.

Concrete pile damage during driving includes crushing at pile head or toe, cracking (vertical or horizontal) of the shaft, loss of concrete cover (spalling) at pile head, and failure of splices. Causes of driving induced pile damage include inappropriate hammer, insufficient cushioning, tight pile cap, misalignment between pile and hammer, driving conditions which are very easy, very hard, or bouncy, obstructions in the ground, and uneven contact between hammer and pile head or between the pile toe and bedrock. Furthermore, piles may have experienced excessive handling stresses which can cause further damage during driving. Hussein and Rausche (1991) reported on piles damaged during installation.

2.3 Design and Construction Control

Aside from unavoidable subsurface conditions, all other factors contributing to pile damage can be controlled with proper engineering and construction workmanship. Proper structural design, manufacturing, curing, transportation, and handling along with choice of suitable driving equipment and installation procedures ensure good foundations. Design always begins with a static soil analysis. Previously, only blow count was observed on site during driving. So called "dynamic formula" (now almost universally discredited for their inaccuracy due to simplifying assumptions) were then used to estimate capacity. Although expensive, static loading tests were often applied to verify the foundation "design". Today, rational analytical procedures such as Wave Equation Programs (Goble and Rausche, 1986) incorporating personal computers with numerical models which analyze the hammer-pile-soil system can easily assess at very low cost the driveability of the pile for both driving stress and capacity considerations. Appropriate hammer size, pile cushion thickness, and driving procedure can be determined by the Wave Equation in the design phase to reduce the likelihood of damage during production pile installation. To confirm the assumptions made in a Wave Equation analysis, dynamic field measurements using the Pile Driving Analyzer (PDA) are routinely performed in the field.

Measurements of pile force and motion under a hammer blow are obtained with easily attached and reusable transducers. These data are processed by the PDA using closed form Case Method solutions to compute pile driving resistance and static capacity, hammer and cushion performance, pile driving stresses (compressive and tensile), and an evaluation of pile structural integrity after each hammer blow (Goble et. al., 1980). The integrity assessment by this so-called "high" strain method can determine both location and extent of pile damage. These dynamic tests are particularly useful for installing concrete piles due to their ability to determine both compressive and tensile driving stresses; knowledge of stresses allows adjustments in the driving system to be made to decrease the potential for pile damage. Over the last 20 years these dynamic tests (which are relatively inexpensive compared with static testing) have become routine with an estimated 2500 different project sites annually having PDA testing for either design verification or quality assurance purposes. An ASTM specification covering this procedure testifies to the benefits of these methods (ASTM, 1989). Other very inexpensive dynamic testing methods used extensively in Europe and increasingly in other parts of the world including the U.S.A. require "low" strain impacts generated by small hand held hammers to evaluate structural integrity of concrete piles after installation (Rausche et. al., 1991).

3. CASE HISTORIES

Millions of concrete piles are installed annually around the world. In the United States, concrete piles are routinely driven and in Florida (over 90% of driven piles are prestressed concrete). The following three case histories illustrate the successful installation of long prestressed concrete piles. Dynamic pile testing was performed in each case and allowed for complete monitoring of the hammer, pile, and soil behavior. Information regarding pile driving stress was used to adjust the level of hammer energy output to avoid pile damage and minimize pile driving time. When high stresses were observed, the pile top cushions were replaced. Dynamic testing also provided information on pile load carrying capability which made pile "overdriving" with its potentially damaging consequences unnecessary. The procedure developed by monitoring the driving of the test piles was used to drive the remaining production piles for each project.

3.1 Case 1

A new major highway around Orlando, Florida included 25 bridges founded on prestressed concrete piles. This case study focuses on one pile that was driven as part of a probe pile driving program. The 118 ft (36 m) long, 18-inch (450 mm) square prestressed pile was driven with a Menck MHF 3-7 single acting hydraulic hammer into silty fine sand. The pile was driven inclined at a batter of 1 in 8. Required ultimate pile capacity was 550 kips (2500 kN). Dynamic PDA measurements were performed during pile driving and also during pile restrike one day later. The Menck hammer used has a manufacturer's rated energy of 50.5 kip-ft (69 kJ), but was used at a reduced energy output during installation to control driving stresses and avoid pile damage. The plywood pile top cushion had a thickness of 9 inches (230 mm) and was replaced once during the driving of the pile. Figure 1 presents a summary of pile installation as a function of pile penetration.

During pile installation, hammer energy output was regulated by controlling ram stroke to assure safe and economical pile driving. In this way, pile tension stresses were kept less than 1 ksi (145 kPa) and pile top compressive stresses less than 3 ksi (435 kPa) during pile driving. Pile driving resistance was generally less than 40 blows per foot (BPF) (130 B/m) and reached 273 BPF (900 B/m) at end of driving. End of drive static capacity was 840 kips (3800 kN) which increased to 1080 kips (4900 kN) by the following day due to soil setup.

Driving subsequent production piles which had the same lengths as the test pile also used reduced hammer energy to control stresses as determined during the testing program. Because the test pile had far more capacity than required, the production piles were driven to less penetration allowing them to be also used as columns to carry the roadway with significant time and cost savings.

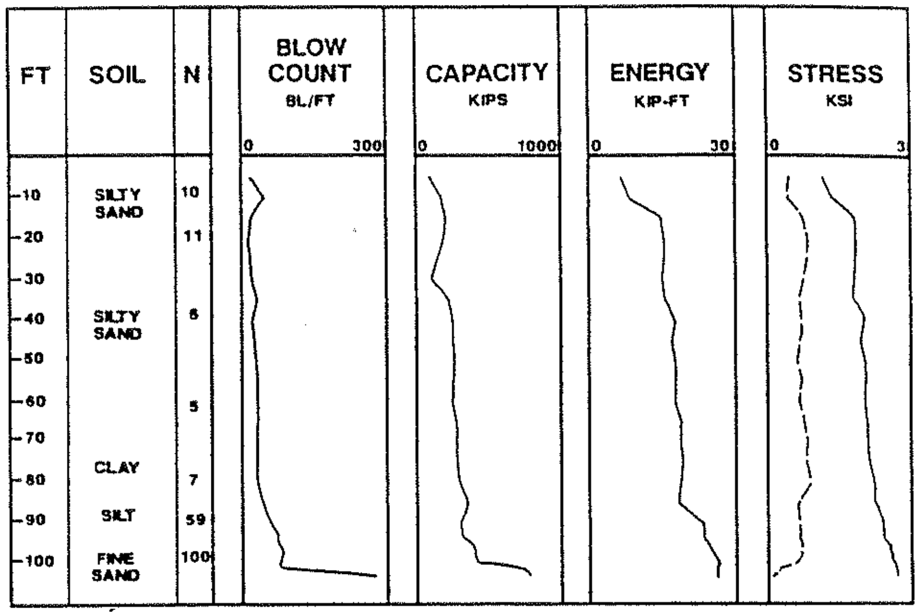

Figure 1: Case 1, 18-inch (450 mm) square pile, 118 ft (36 m) long, driven with a hydraulic hammer.

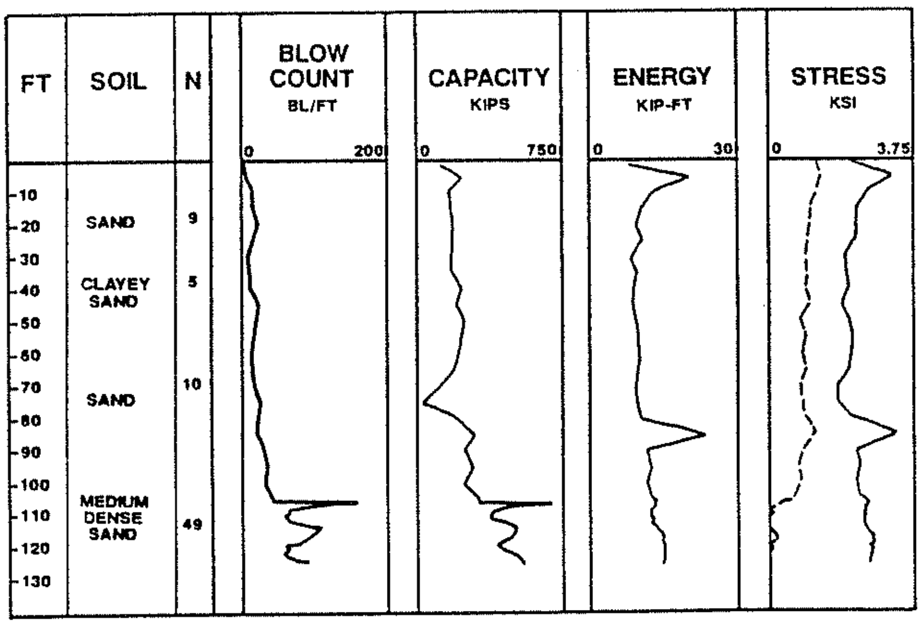

Figure 2: Case 2, 18-inch (450 mm) square pile, 138 ft (42 m) long, spliced pile driven with a diesel hammer.

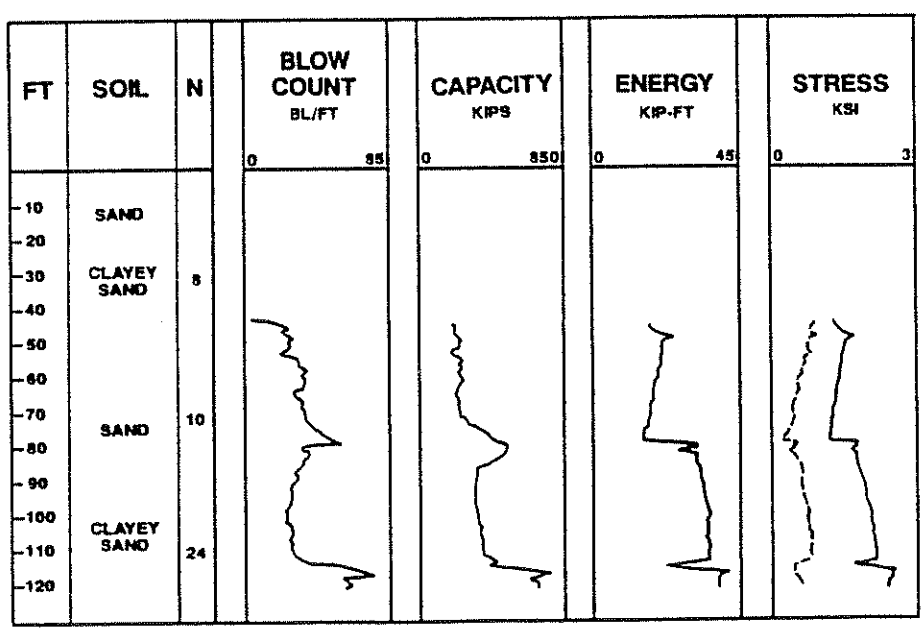

Figure 3: Case 3, 30-inch (750 mm) square with 18-inch (450 mm) circular void pile, 135 ft (41 m) long, driven with an air hammer.

1 ft = 0.305 m, 1 kip = 4.45 kN, 1 ksi = 6.89 MPa

3.2 Case 2

At another bridge site location near Orlando, Florida, 18-inch prestressed concrete piles were driven using a Delmag D46-32 open ended diesel hammer which has a ram weight of 10.12 kips (46 kN) and four fuel pump settings which control the hammer energy output potential. At maximum fuel setting, the hammer has a rated energy of 113.2 kip-ft (157 kJ). The pile was spliced and had a total length of 138 ft (42 m). The first section driven was 118 ft (36 m) long to which a 20 ft (6 m) section was added using a dowel and epoxy splice. Figure 2 presents a summary of pile installation along with soil profile. Pile top cushion consisted of 6.75 inches (170 mm) of plywood. At the end of driving of the first section and a penetration of 106 ft (32 m), pile driving resistance was 43 BPF (140 B/m) and static capacity 320 kips (1450 kN). Required ultimate pile capacity was 500 kips (2270 kN). Pile top cushion thickness was increased to 9 inches (225 mm) after splicing. The pile showed a substantial capacity increase during the wait required for splicing. Towards the end of final driving, after splicing, pile driving resistance was 156 BPF (510 B/m) and static capacity 540 kips (2450 kN). Utilizing information from dynamic measurements during pile driving, the hammer fuel settings were adjusted to limit pile driving stresses to safe levels. During the entire installation process, pile tension and compression stresses did not exceed 1.2 and 3.3 ksi (170 and 480 kPa), respectively.

3.3 Case 3

Sixteen prestressed concrete piles were driven and tested as part of a preconstruction test program to determine pile driveability and obtain foundation design parameters at a bridge site in western Florida. The piles were 30-inch (750 mm) square sections with an 18-inch (450 mm) circular void throughout their length. Pile lengths ranged between 45 ft (14 m) and the 135 ft (41 m) pile considered here. Required ultimate pile capacity was 750 kips (3400 kN). Pile driving was accomplished by a Conmaco 300E5 single acting air hammer which has a ram weight of 30 kips (136 kN) and was adjustable to both a 1.5 ft (0.45 m) or a 3.0 ft (0.90 m) stroke, corresponding to rated energies of 45 kip-ft (62 kJ) and 90 kip-ft (125 kJ), respectively. Pile top cushion consisted of 9 inches (225 mm) of plywood. Again, dynamic pile monitoring was performed throughout pile installation and also during restrike a few hours later. Pile driving testing results are summarized in Figure 3 along with soils information. The pile penetrated under its own weight and that of the hammer to a depth of 40 ft (12 m). The hammer at the lower stroke then drove the pile an additional 45 ft (14m). At this point, the tension stresses had been reduced due to sufficient friction such that the stroke was increased to the full 3 ft (900 mm). The pile was driven to a final penetration of 115 ft (35 m) and a driving resistance of 60 BPF (200 B/m) corresponding to a PDA computed pile capacity of 760 kips (3450 kN). Testing during a restrike a few hours later showed the pile static capacity increased to 990 kips (4500 kN). During the entire pile driving sequence, tension stresses were less than 0.7 ksi (100 kPa) and compression stresses less than 2.5 ksi (360 kPa). This procedure was adopted also for production piles to limit pile driving stresses and avoid potential pile damage.

4. CONCLUSION

Due to their strength, serviceability and low cost to durability ratio, precast prestressed concrete piles are often the preferred alternative deep foundations. Concrete piles with lengths over 100 ft (30 m) are routinely used around the world. In the U.S.A., prestressed piles are the predominate concrete pile type. The mechanics of impact pile driving are now well modeled by wave equation programs allowing for rational methods to assess installability of piles. In the design phase, this numerical modeling can realistically assess the driveability of a hammer pile combination to the desired ultimate capacity. In the field, electronic pile driving monitoring provides information on capacity, driving stresses and hammer performance that aids in establishing safe and economical installations. This paper presented discussions on driving prestressed concrete piles along with three case histories illustrating the effectiveness of dynamic pile testing in successful installation of long piles.

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