DRIVING STRESS CONTROL DURING THE INSTALLATION OF PRECAST PRESTRESSED CYLINDRICAL CONCRETE PILES

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Abstract

The Pile Driving Analyzer (PDA) was developed to meet specific requirements of projects similar to that described in this paper. Knowledge of the driving stress magnitudes during driving and the capability to control them is considered important for safe and adequate installation of the piles. Driving stresses, both tension and compression, were of primary concern for the project's 36-inch (915 mm) diameter precast prestressed hollow cylindrical concrete piles. A Conmaco 5300 single acting air hammer having dual stroke capability (3 and 5 ft; 915 and 1525 mm) was used to drive the piles. Specifications required that driving stresses be kept below the limits recommended by the U.S. Federal Highway Administration (FHWA).. This was achieved by measuring force and acceleration near the top of several piles and the processing of these measurements by the PDA for every blow during pile driving to yield both compression and tension stresses. The PDA field calculated compression and tension stresses were compared to driving stress limits recommended by FHWA. The stresses were used to decide when to change the hammer stroke and pile top cushion. Actual field measurement and analysis results of selected piles are presented.

Introduction

The capability to measure force and acceleration near the pile top during driving has become a routine practice (Likins et al. 1988). These

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measurements are processed by the Pile Driving Analyzer (PDA) which evaluates pile capacity, pile driving stresses, pile integrity and driving system performance (Goble et al. 1980; Rausche et al. 1985). One advantage of the PDA is its flexibility to adopt to specific requirements of any pile installation project. Some project specifications require piles to be driven to specific penetrations to satisfy design requirements, and in some cases this requires larger hammers to be used. Large hammers, however, may overstress the pile during driving. In this project, the piles were to achieve specified penetrations and driving stresses were a primary concern. Knowledge of stresses during driving and the capability to control them were considered important for safe and adequate pile installations. Therefore, dynamic pile testing using the PDA was specified for several piles to monitor the driving stresses. The PDA results were reviewed in real time and adjustments to hammer stroke and/or replacement of cushion were made to limit driving stresses within the recommended values.

Background

During a PDA test, two strain transducers are bolted near the pile top. The average strain is computed and converted to force by multiplying the strain by the product of elastic modulus times the pile cross sectional area. From the PDA field measurements, the maximum pile top force during driving can be obtained directly. Dividing this force by the pile cross sectional area yields maximum compression stress, CSX, at the measurement location. The maximum stress for either strain transducer, CSI, can be obtained and comparison with CSX reflects a measure of the uniformity or bending of the impact. The maximum tensile stress in the pile can be calculated utilizing the pile top PDA measurements. First, the upward, Wu, and downward, Wd, traveling wave magnitudes are computed from

$$Wu = 1/2\ [F(t) - Zv(t)] \tag{1}$$

$$Wd = 1/2\ [F(t) + Zv(t)] \tag{2}$$

where F(t) and v(t) are pile force and velocity record at the measurement location and pile impedance Z (= EA/c) is calculated from cross sectional area A, elastic modulus E, and wave propagation speed c. The maximum net tension, CTN, can then be computed by superimposing the maximum upward tension force (Wu; which arrives at time 2L/c after the peak input) with the minimum downward compression force (Wd; during the first 2L/c time); L is the length of the pile below the measurement location. Dividing CTN by the pile cross sectional area yields the pile maximum tension stress, TSX.

Driving stresses are related to the energy delivered to the pile. This energy can be calculated from the work done on the pile.

$$E(t) = \int F(t)\ v(t)\ dt \tag{3}$$

The maximum value of this integration, EMX, is the maximum transferred energy to the pile.

Concrete piles are generally susceptible to transverse cracks and damages which can occur during easy driving from high tension stresses. Tension is mostly resisted by the reinforcing steel and/or prestressing strands and to a lesser degree by the tension capacity of the concrete itself. According to the U.S. Federal Highway Administration (FHWA) recommendation, the driving stress limit in tension for prestressed piles is given by

$$F_t = 3\sqrt{f'_c} + f_{pe} \tag{4}$$

where F_t is the recommended tension stress limit (in psi), f'_c is concrete compressive strength (in psi), and f_{pe} is effective prestress after losses (in psi).

Compression stresses usually reach a critical stage during hard driving. The recommended limit by FHWA (Vanikar, 1986) is given by

$$F_c = 0.85f'_c - f_{pe} \tag{5}$$

where F_c is the recommended compression stress limit (in psi) recommended by FHWA. In the described project, compression and tension stresses, as well as transferred energy to the piles, were continuously monitored by the PDA in real time and necessary steps taken to minimize the possibility of pile damage.

Project and Pile Information

The project involved driving piles for several piers and abutments for a major interchange and elevated roadways crossing a designated wetland area. The 36 inch (915 mm) diameter precast prestressed hollow cylindrical concrete piles had lengths varying from 52 to 92 ft (16 to 28 m). Each pile had a uniform wall thickness of 6 inches (150 mm) and the corresponding cross sectional area of each pile was 566 in^2 (3,652 cm^2). Some piles were designed to be installed at an inclination. Concrete strength, f'_c, of 7000 psi (48 MPa) was used and the effective prestress after losses, f_{pe}, was reported to be 1060 psi (7.3 MPa). The recommended allowable stress limits according to the FHWA was 4.62 ksi (31.8 MPa) in compression and 1.31 ksi (9.0 MPa) in tension. These stresses were used as limiting values to driving and remedial measures were taken as the driving stresses approached these limiting values.

Hammer Information

A Conmaco 5300 hammer drove the piles. This hammer has a ram weight of 30 kips (134 kN) and with a maximum stroke of 5 ft (1.52 m), it has a maximum rated energy of 150 ft-kips (203 kJ). The hammer can also operate at a reduced stroke of 3 ft (915 mm) yielding an energy rating of 90 ft-kips (122 kJ). The reduced stroke was always used at the beginning of driving. The hammer cushion consisted of aluminum and micarta discs while the pile top was protected by a 10 inch (250 mm) thick plywood cushion. The hammer was assembled in a short offshore lead system.

Soil Information

Several soil boring logs were taken at the site. The soil conditions can be generalized as organic material in the upper zone followed by an upper thick layer of medium to fine sand with some gravel and silt. Below the sand layer is a zone of silty clay and then a lower layer of coarse to medium sand with some silt. The thickness of the layers described above varied across the site but the piles were designed to be embedded in the lower sand layer.

Pile Installation and Monitoring Results

Prior to pile driving, a pair of strain transducers and accelerometers were attached near the top of each monitored pile. The PDA then processed the force and acceleration data and computed energy transferred to the piles and both tension and compression stresses. These results were displayed on the LCD screen of the PDA in real time. Typical force and velocity records obtained by the PDA for Pile 1 at blow numbers 162, 231, and 593 are shown in Figure 1. A summary of results for this pile is shown in Figure 2. The hammer was always started with the short stroke for every pile driven. The tension stresses calculated by the PDA were viewed in real time and a determination was made as to when to increase the hammer stroke based on the FHWA recommended driving stress limits. The hammer stroke was switched to the long stroke only after the PDA indicated tension stresses much less than the FHWA recommended limit of 1.31 ksi (9.0 MPa). As the tension stresses increased, for some piles the stroke had to be reduced again to the short stroke as shown in Figure 3. In many cases, the measures taken to maintain tension stresses below the recommended limit included reducing the stroke as well as simultaneously changing pile top cushion.

When the driving resistance increased, compression stresses approached the FHWA limiting value of 4.62 ksi (31.8 MPa). This necessitated a change of pile top cushion. On some occasions the pile top cushion on the inclined piles compressed unevenly (more on the low side of the piles) because of alignment problems between the hammer and the inclined piles. These unevenly compressed cushions adversely affecting the cushion integrity and its ability to adequately protect the piles and resulted in relatively high compression stresses on one side of the piles. The comparison of CSX and CSI maximum stresses can be used to assess hammer pile alignment or if the pile cushion is unevenly compressed. Figure 1 demonstrates that for blows 162 and 232 that the CSI and CSX values were similar and thus no significant bending. For blow 593, however, the CSI stress is well above the CSX stress, indicating an unevenly compressed cushion. This also warranted a change of pile top cushion. The pile cushion was therefore replaced at blow number 600, as shown in Figure 2, and inspection of the cushion confirmed that it was indeed unevenly compressed. Typical example summaries of PDA results are presented in Figures 2 to 4. The figures are labeled to indicate the actions taken during the progress of the installation of selected piles.

Nearly one third of the piles installed at the site were monitored over a one year period to control driving stresses. For the remaining piles not dynamically monitored, criteria was established as to when to change the stroke and/or pile top cushion. Based on the test results, the criteria established were:

a) The hammer stroke was switched to full stroke generally after blow counts exceeded 30 blows per foot (98 blows per meter).

b) If at any point during driving with the full stroke, the blow counts decreased to less than 20 bl/ft (65 bl/m), the hammer stroke was reduced to the short stroke.

c) The pile top cushion was to be replaced after approximately 250 blows at full hammer stroke unless clear indication of cushion wear out or severe bending was detected earlier; replacing the cushions was considered far preferable to breaking a pile, considering the extremely high cost of a single pile.

Conclusions

The Pile Driving Analyzer was effectively used to control driving stress during the installation of several 36 inch (915 mm) diameter precast prestressed hollow cylindrical concrete piles. Both tension and compression driving stresses were monitored during actual driving and, based on the FHWA recommended driving stress limits, indicated when to increase or decrease the hammer stroke. The PDA results were also used to determine appropriate frequency to change pile top cushion. Communication between the contractor, engineer and owner was clearly established and all concerned parties worked together to complete the project successfully.

References

Likins, G. E., Hussein, M., Rausche, F., 1988. Design and Testing of Pile Foundations. Proceedings Third International Conference Application of Stress Wave Theory to Piles, Ottawa.

Goble, G., Rausche, F., Likins, G. E., 1980, The Analysis of Pile Driving. State of the Art. Proc. First International Conference Application of Stress Wave Theory to Piles, Stockholm.

Rausche, F., Likins, G.E., and Miner, R., 1985. The Performance of Pile Driving Systems. Main Report, Vol. 1 to 4, Federal Highway Administration Contract # DTFH 61-82-C-00059, Washington D.C., USA.

Vanikar, S. N., 1986. Manual on Design and Construction of Driven Pile Foundations. U. S. Department of Transportation, Federal Highway Administration, Demonstration Projects Division, Washington, D. C., pp 310-320.

SI CONVERSION FACTORS

To convert	To	Multiply by
inches (in)	meters (m)	0.0254
feet (ft)	meters (m)	0.3048
pounds (lbf)	newton (N)	4.448
kips (1000 lbf)	kilo Newton (kN)	4.448
foot-pounds (ft-lbf)	joules (j)	1.356
foot-kips (ft-kips)	kilo Joules (kJ)	1.356
pounds/in^2 (psi)	Pascal (Pa)	6894
kips/in^2 (ksi)	Mega Pascal (MPa)	6.894

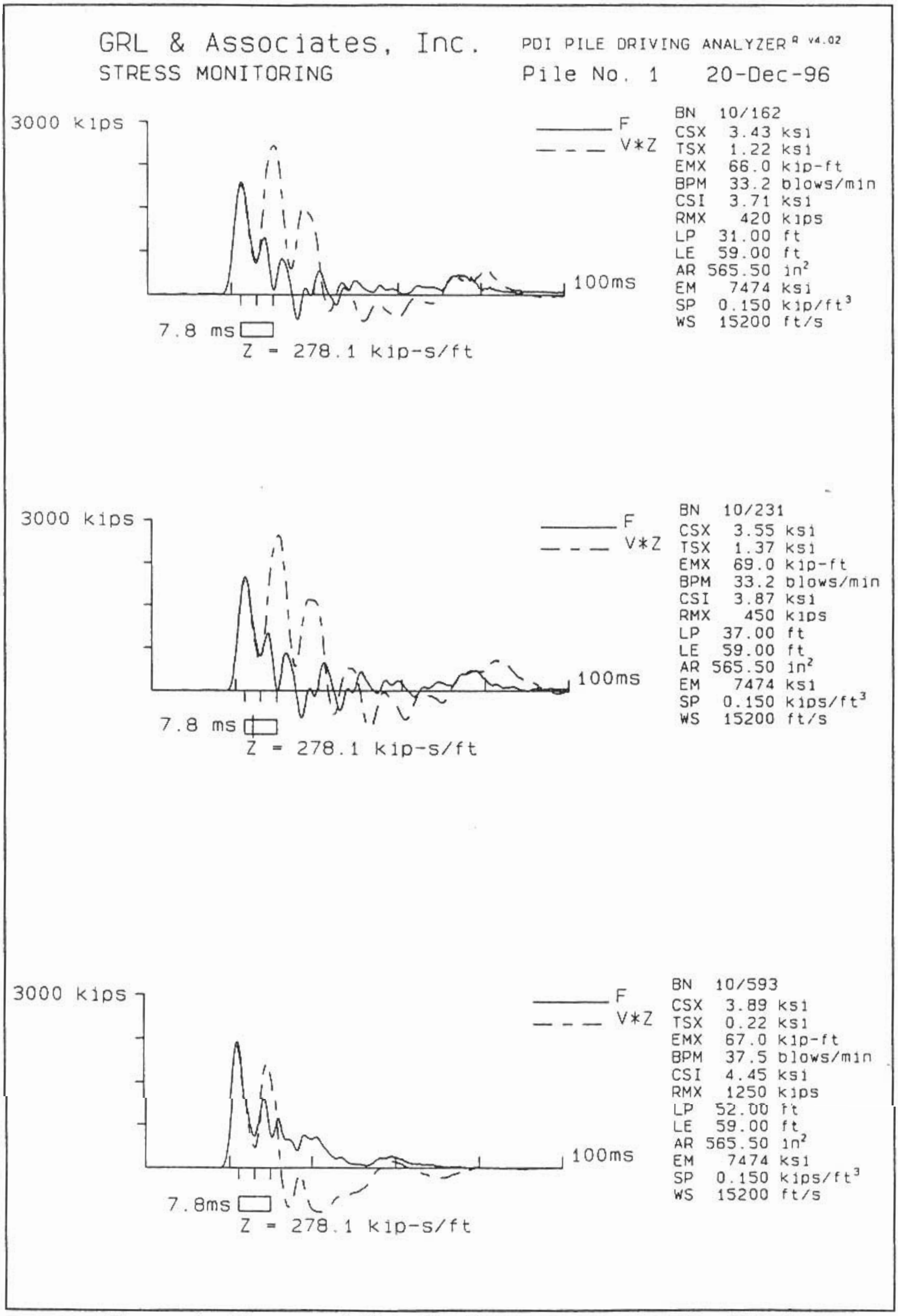

Figure 1: Force and Velocity Recorded by PDA for Pile 1

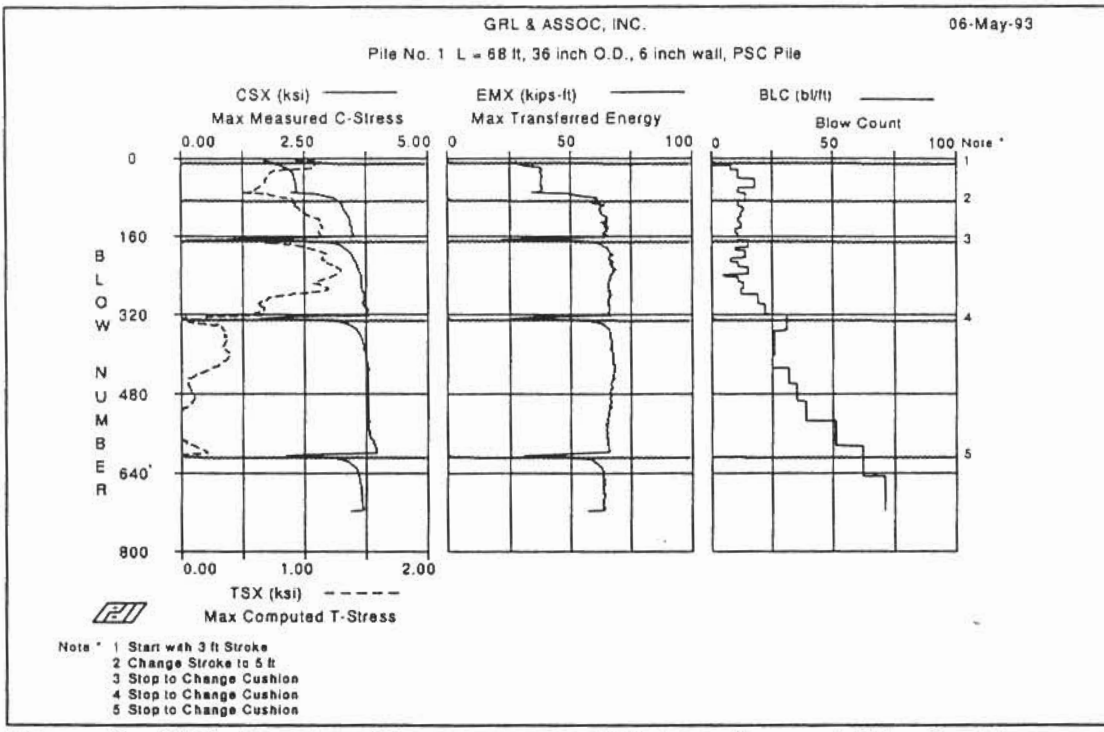

Figure 2: PDA Results, Blow Counts, and Locations of Pile Cushion and Stroke Changes, Pile No. 1

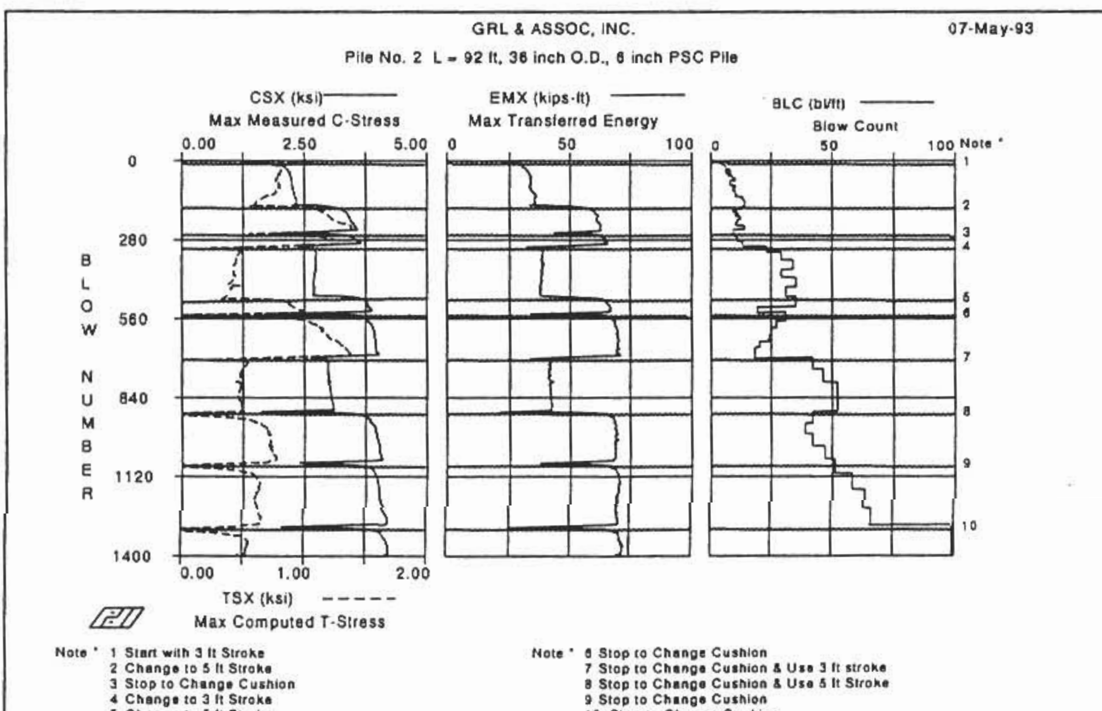

Figure 3: PDA Results, Blow Counts, and Locations of Pile Cushion and Stroke Changes, Pile No. 2

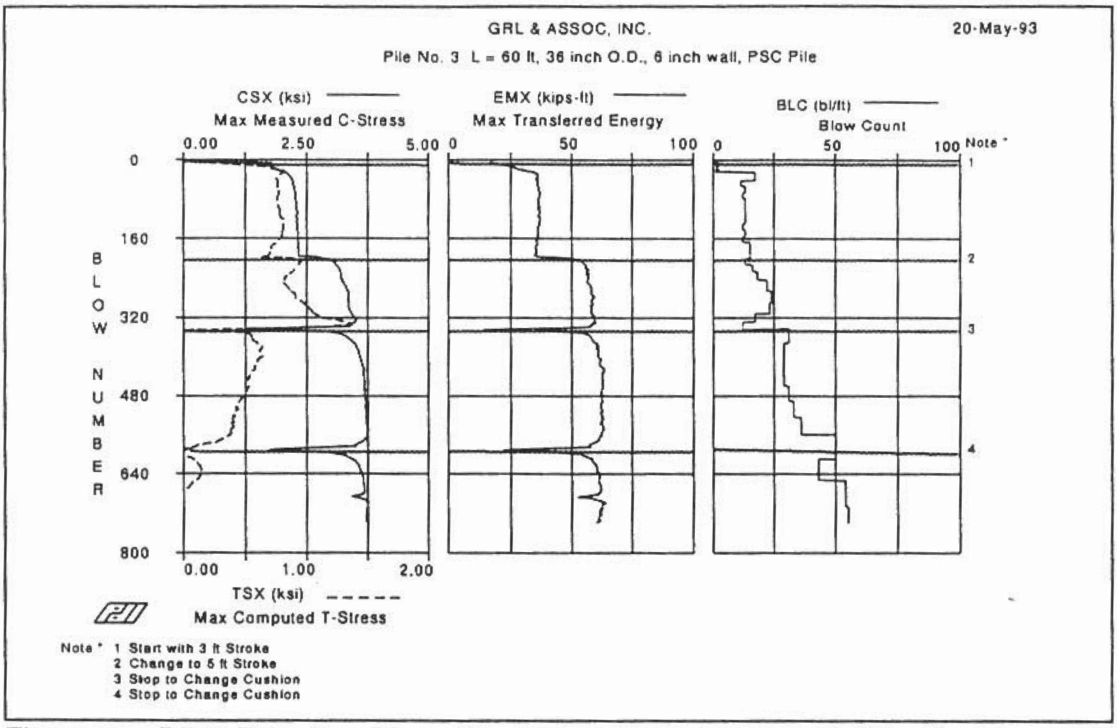

Figure 4: PDA Results, Blow Counts, and Locations of Pile Cushion and Stroke Changes, Pile No. 3