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Augered cast-in-place pile testing in Southern California

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ABSTRACT: This paper presents the results of field observations and testing of 1,075 augered cast-in-place piles installed on a southern California site underlain by alluvial deposits. Components of the quality assurance plan are reviewed: installation records, integrity testing, and static load testing. A pile shorter than the production piles was installed to calibrate the wave speed and the amplification factor to facilitate the interpretation of the sonic tests. Evaluation of the pile shape below ground using wave equation modeling is discussed. Pile behavior under both low and high strain is analyzed.

1 INTRODUCTION

A total of 1,075 auger-cast piles were installed between March 10 and September 11, 1992, to support a central chiller plant and its cogeneration facilities at the University of California, Los Angeles Campus (see Fig. 1). Observation of pile installation, as well as nondestructive low-strain integrity testing, was performed by Harding Lawson Associates (HLA). Parsons Municipal Services, Inc. (PMSI) requested these services as part of the field quality control during installation of auger-cast piles. Static load testing was also performed on two of the piles.

Because a portion of the facilities were under jurisdiction of the California Administrative Code, Title 17, Chapter 8, Safety of Construction of Hospitals, design and construction were reviewed by the California Division of Mines and Geology, the Office of the State Architect, and the Office of Statewide Health Planning and Development.

2 SUBSURFACE CONDITIONS

Based on exploratory borings drilled at locations shown on Fig.1 and summarized on Fig.2, (HLA,

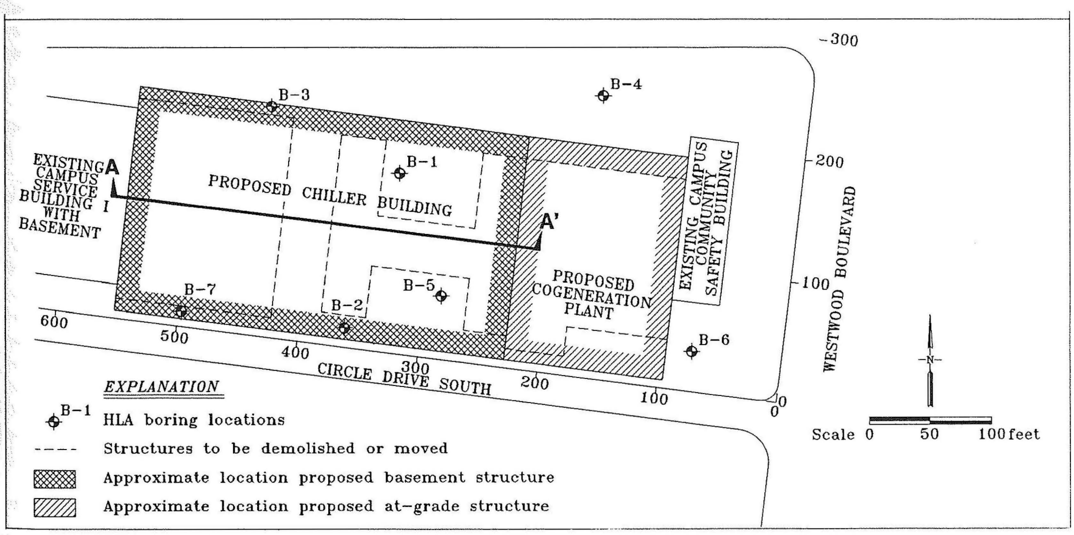

Fig. 1 - Site Plan

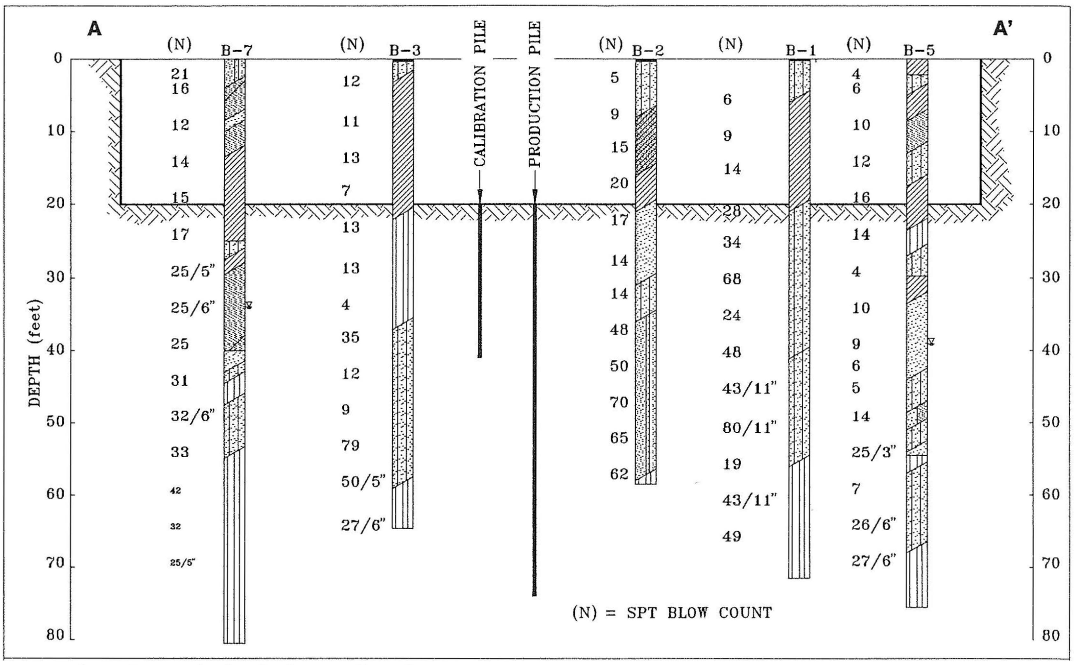

Fig. 2 - Geotechnical Cross-Section

1988 and 1989), the soils are quite variable, which is characteristic of alluvial materials. Deposit thicknesses, blow counts, and corresponding densities and shear strengths vary widely among borings. For foundation design purposes, the subsurface materials were divided into four strata as described below:

1. The upper 6 to 18 feet generally consisted of uncertified fill material including loose to medium-dense sands, silty sands, and clayey sands (SP, SM, and SC) with occasional lenses of sandy clay (CL). These surficial deposits have relatively low densities and shear strength.

2. Below the fill, upper fine-grained deposits were encountered in thicknesses between 2 and 30 feet extending to a maximum depth of approximately 36 feet. These medium-stiff to very-stiff sandy clays and sandy silts (CL and ML) are compressible and have low to moderate shear strengths.

3. Below the upper fine-grained deposits, loose to very-dense silty sands, clayey sands, and poorly graded sands (SM, SC, and SP) were encountered in thicknesses between 12 and 40 feet, extending to a maximum depth of approximately 68 feet. Lenses of sandy clay were also encountered in this layer. Blow counts varied widely within this stratum indicating highly variable densities.

4. The lower stratum encountered below a depth ranging from approximately 40 to 68 feet consisted of very stiff to hard silts extending to the depth drilled. These fine-grained deposits are moderately compressible and have moderate to high shear strengths.

Groundwater was encountered during the field investigation at depths between 34 and 60 feet.

3 AUGERED CAST-IN-PLACE PILES

Augered cast-in-place piles are considered in southern California as a relatively modern variation of the more commonly used drilled cast-in-place piles. The continuous hollow-stem flight auger is viewed as a temporary casing maintaining the hole open. The augered cast-in-place piles are constructed by advancing the continuous-flight auger into the ground to the required depth. At the full depth, grout or fine aggregate concrete is pressure injected down the core of the hollow-stem auger. The auger is then pulled out of the ground as grout fills the void left by the auger. Reinforcement is added at this stage.

Because the owner was concerned about vibration effects on adjacent structures, and the subsurface conditions indicated potential for caving of unsupported holes, augered cast-in-place piles were deemed the most suitable deep foundation system.

Due to the absence of a continuous, dense end-bearing stratum, most of the pile capacity had to be provided by side friction rather than tip resistance. The allowable compression capacities were estimated based on the SPT blow counts for the at-grade eastern cogeneration plant and for auger-cast piles installed to support the basement-level chiller plant structure. The specified pile diameter was 18 inches and the length was generally 55 feet. The design allowable static downward capacity was 72.5 tons.

It is widely recognized that the successful application of augered cast-in-place piles depends on the quality of construction and indirectly on procedures to monitor it. It was therefore recommended to establish detailed specifications for the selection of a qualified specialty contractor. As part of the quality control process, it was recommended that a vertical pile load test be conducted on one of the piles installed during the early phases of the project. Integrity testing of the piles was also recommended to establish the structural integrity of the piles during the initial construction phases.

The auger-cast piles were constructed by Shoring Engineers, Inc., using a crane-mounted, 18-inch-diameter, continuous-flight, hollow-stem auger for drilling and a concrete pump and high-pressure hose for grouting. A spiral-reinforced steel cage was inserted into the fresh concrete in the top 22 feet of the pile shaft. In addition, for tension piles and reaction piles, a central reinforcing bar was placed through the entire pile length prior to grouting.

4 FIELD OBSERVATION AND TESTING

4.1 *Pile Installation Observations*

During drilling, time and soil types were recorded at 5-foot intervals as the hollow-stem auger was advanced. During grouting, the number of pump strokes, grout line pressure, and time were recorded at 5-foot intervals as the hollow-stem auger was withdrawn.

The concrete volume per stroke was calibrated prior to pile construction by counting the number of strokes needed to fill a wooden box with an interior volume of approximately 0.38 cubic yard. Pump stroke calibration indicated that a minimum of 16 strokes was required to construct each 5-foot increment of an 18-inch-diameter pile. This volume corresponded to approximately 115 percent of the nominal volume of the pile.

Based on a review of the grouting records, a rating for each pile was assigned based on criteria such as minimum grout strokes, grout pressure (125 to 150 pounds per square inch [psi]), uniformity in grout strokes, and grouting/auger withdrawal time rate. Pile grout rating criteria were established as follows:

- Installation Rating A - The grouting of the pile met the criteria discussed above,
- Installation Rating B - The grouting records indicated that pile imperfections could be judged sufficient to affect the pile allowable load, and
- Installation Rating C - The grouting records indicated that the pile was deemed to have serious defects and should be rejected.

Based on the grouting records collected, all piles were considered satisfactory (Ratings A and B), except for three piles, which were replaced.

4.2 *Pile Integrity Testing*

The integrity tests consisted of striking the pile head with a hammer to generate a compression wave (Holeyman, 1992). Pile head velocity and impact force were recorded and interpreted to help evaluate the integrity of the pile. The testing equipment included an instrumented hammer and an accelerometer located at the pile head (see Fig. 3a). The contractor troweled the concrete before setting to provide the flat, smooth, horizontal surface required at the pile head to perform the test. The instruments were connected to a digital dynamic signal analyzer with digital storage, filter, and amplification functions to facilitate field data validation. The equipment used to perform the test was a "PIT collector", manufactured by Pile Dynamics Inc.

Integrity tests performed at the site indicated that within a period of approximately 10 days, the older the concrete, the clearer the measured signals. Generally, a minimum delay of 3 days between installing and integrity testing the piles was found to provide clear signals and still permitted to provide timely information to the contractor before concreting pile caps.

The integrity records were evaluated based on two plots for each pile as shown on the example provided on Fig. 3. The top plot (3b) shows the raw velocity and force signals as measured by the accelerometer and instrumented hammer as functions of depth, while the bottom plot (3d) shows the results of the filtered and exponentially amplified velocity signal as a function of depth. Between the two plots is a sketch (3c) of the pile length and the depth-dependent amplification function used to help compensate the damping of the wave energy as the wave travels down the pile.

To help clarify the origin of the generally noted upward trend of the velocity signal at a depth of approximately 20 feet, which approximately coincided with the bottom of the spiral reinforcing cage, a 22-foot-long calibration pile was installed. That pile was designed to produce a reference signal corresponding to a 100-percent reduction of the pile shaft at 22 feet. As demonstrated on Fig. 3d, testing of this calibration pile resulted in the calibration of the wave speed and amplification factor. Based on a sharp reflection of the signal, an average compression speed of 11,500 feet per second was ascertained. By matching the size of the reflective pulse to the initial impact pulse, an average amplification factor of 30 was selected as a default value to interpret the 55-foot-long pile test records.

Test records were evaluated using the "Beta-Method" (Rausche and Goble, 1979) that allows a rough quantification of the relative reduction of shaft impedance based on the relative amplitude of the reflected pulse.

Pile rating criteria relative to integrity testing were established as follows:

- Integrity Test Rating A - Absence of major reflections, except for the one marking the pile toe at a depth of 55 to 65 feet,
- Integrity Test Rating B - Presence of significant positive reflections at depths of less than 55 feet and the absence of a clear reflection at the pile toe, and
- Integrity Test Rating C - Presence of a clear and strong reflection at a depth of less than 55

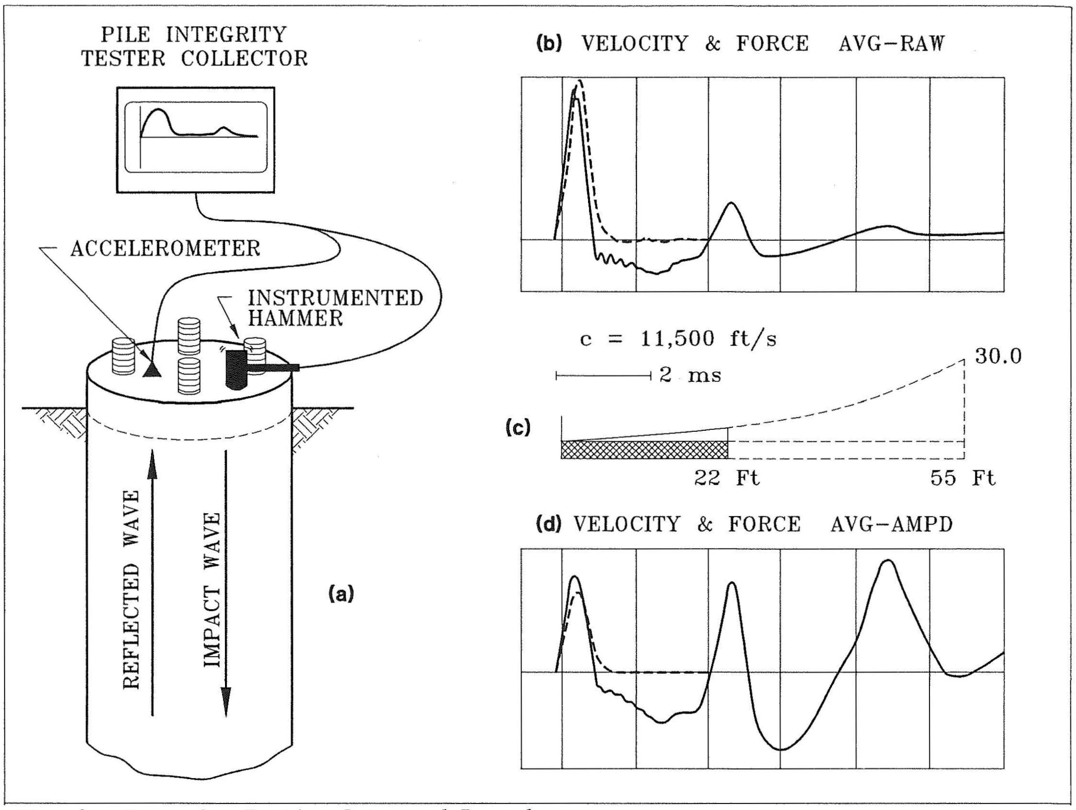

Fig. 3 - Integrity Testing Setup and Procedure

feet and absence of a reflection at the pile toe.

For the purpose of the integrity test rating, a significant positive reflection was defined as corresponding to a relative reduction of the shaft impedance of at least 20 percent, as evaluated using the "Beta Method." This level was chosen in consultation with the project structural engineer and was based on comparison of the structural capacity of the pile shaft to the pile maximum service load.

Based on review of the grouting records and integrity test results, a total of 29 piles were rated B. No piles were rated C. Piles that were rated B based on grouting records were generally rated A based on integrity test results, except for one pile, which was rated B based on grouting records and also rated B based on integrity test results.

4.3 *Pile Static Load Testing*

A static pile load test was performed on Pile PC 17-9 on March 25 and 26, 1992. Testing procedures were in general accordance with ASTM Test Method D, 1143-81, Standard Loading Procedure. Pile load test results are summarized on Fig. 4. The maximum deflection observed under a 145-ton load was approximately 0.15 inch, confirming a safety factor of at least 2.

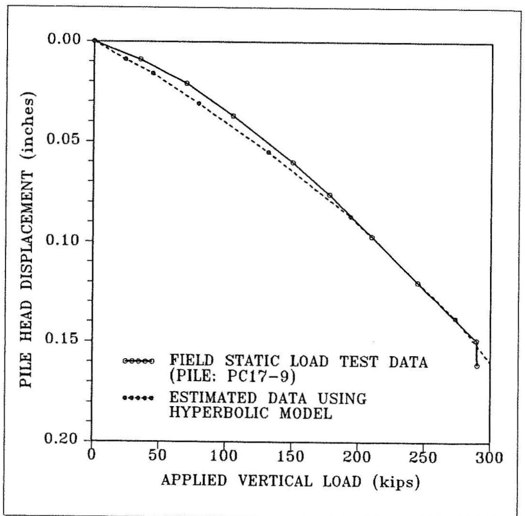

Fig. 4 - Load Test Results and Evaluation

5 PILE BEHAVIOR INTERPRETATION

The behavior of the augered-cast-in-place piles under axial load can be approached from the many angles afforded by the data collected onsite: low-strain behavior can be evaluated from the seismic refraction survey conducted as part of the geotechnical investigation and the integrity testing of the piles, while the high-strain behavior can be evaluated from the exploratory borings data and the pile load test.

5.1 *Low-Strain Behavior*

The results of the seismic refraction survey conducted at the site indicated a shear wave velocity of 760 feet per second (ft/s) down to a depth of 36 ft and 2,300 ft/s at greater depth. Based on the unit weight of the soil, these results translate into low-strain shear moduli of approximately 2,100 and 21,000 kips per square foot (ksf), respectively.

A common treatment of integrity records consists of amplifying the low-strain velocity signal using an exponential function increasing with time, such as e^{At}. This treatment is aimed at counteracting the attenuation of the signal as it travels through the shaft. It can be shown that the exponent A should be, in theory, proportional to the shaft-specific radiation damping: $\varrho_s v_s$ where ϱ_s = soil specific mass and v_s = shear wave speed in the soil. Based on the results of the seismic survey, one could anticipate the shaft specific radiation damping above and below a depth of 36 feet to be approximately 2.8 and 9.3 ksf/fts^{-1} respectively.

Pile and soil behavior can be modeled using a wave equation computer simulation of the event recorded during a dynamic test. The adjustment of the model parameters is guided by matching the calculated velocity with the measured velocity, while the model is subjected to the measured force imposed at the pile head.

Such a model was developed to gain insight into the more detailed interpretation of the integrity test. The results of the adjustment using the PITWAP procedure (Rausche, Likins, and Shen, 1992) for the 22-ft long pile are shown in Fig. 5a. An exponential amplification reaching 3.5 at a 22-foot depth was used to fine-tune the signal match. As can be observed on Fig.5a, the adjustment is both satisfactory and significant. It should be noted however, that the shear modulus of the soil necessary to explain the measured attenuation of the signal was approximately 850 ksf, i.e., 40 percent of the value determined by the seismic survey.

A possible explanation for the discrepancy between experimental and theoretical damping may reside in the low-strain quality of the fresh bond between the shaft and surrounding soil. It is possible to envision a micrometric gap between concrete and soil as a result of installation or concrete shrinkage. On the other hand, the magnitude of the vertical movement (typically a few microns during integrity test impact) may be insufficient to mobilize shear stresses attributable to roughness effects. These considerations are limited to the very low displacement range and should not be generalized to the larger strain behavior.

Another model was used for the 55-ft long piles, for which a sample adjustment is shown on Fig. 5b. Although it is possible to construct apparently satisfactory matches at low amplification factors, the task proved to be much more arduous at more realistic amplification factors. Difficulties facing the modeler are the loss of accuracy of strongly amplified signals and the potential numerical instability of models with an slenderness ratio larger than 40.

5.2 *High-Strain Behavior*

Load-settlement behavior of a single pile can be modeled using the algorithm proposed by Coyle and Reese (Coyle and Reese, 1966). Hyperbolic soil-pile interface transfer functions were used to model the pile vertical deformation behavior and match it with the deformation measured in field.

The satisfactory match shown on Fig. 4 was obtained using the following parameters: a uniform ultimate unit skin friction of 1.6 ksf with an initial tangent modulus of 20 kips per square foot per inch (ksf/in) and an ultimate unit base resistance of 100

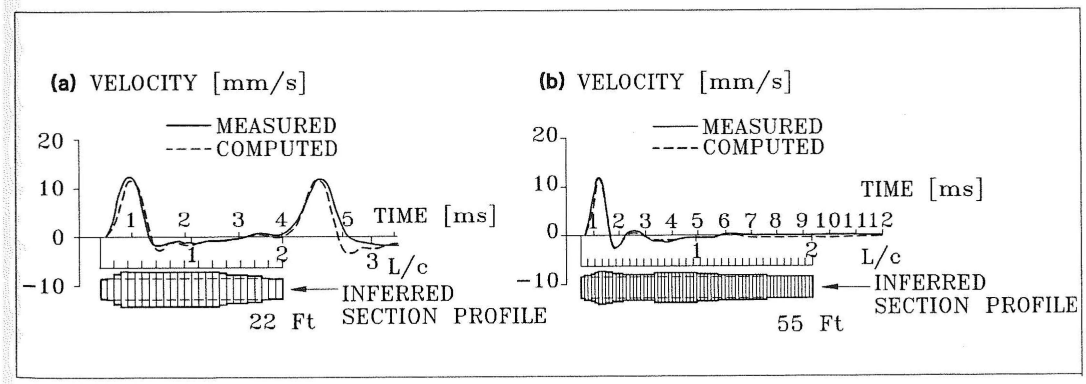

Fig. 5 - Pile Shape Evaluated from Signal Matching

ksf with an initial tangent modulus of 3,000 ksf/in. These parameters correspond to an initial tangent sheer modulus of 850 ksf, which compares well with the value inferred from the observed attenuation of the integrity test signal.

6 CONCLUSIONS

Based on observations during installation and review of the grouting records, the piles as per the final as-built drawings were deemed installed in general accordance with the geotechnically related project specifications.

Results of the static load test indicated that the tested pile could safely carry the design load, and no modification to pile design was necessary. The test pile was found to have a safety factor of more than 2, which was used in the original design of the piles.

We understand that the structural engineer evaluated, on a case-by-case basis, the structural capacity of the reduced shaft sections identified by the integrity tests. The structural engineer then accepted the piles as appropriate based on the actual loading conditions.

7 ACKNOWLEDGMENTS

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