DYNAMIC TESTING IN PILE DRIVING TEST PROGRAMS AND PRODUCTION

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Abstract

A massive earth dam constructed near Sardis Mississippi in the 1930's has undergone remedial treatment to insure the integrity of the dam and reservoir during a massive earthquake. Several studies of the underlying soils and the site's close proximity to the New Madrid earthquake fault zone indicated the need for remediation of the dam against lateral movement. A very extensive study of various remedial techniques indicated that the use of driven prestressed concrete piles was the most cost effective and provided the most reliable solution to the problem. A test program located on the accessible downstream side of the dam which included dynamic testing and analysis was designed to assess the driveability of different pile sizes and pile spacings. Based on these results, a design for the installation of 2,600 piles on the upstream side of the dam was conceived. This paper describes the dynamic testing of the piles with the Pile Driving Analyzer, which included driving and testing of piles under water from a barge. Subsequent CAPWAP analysis of the data, and extensive wave equation analysis were instrumental in assessing and modifying procedures for the successful and economic installation of the production piles.

Introduction

The San Fernando Earthquake in California on 9 February 1971 caused a major slide of the Lower San Fernando Dam which alerted the engineering community to the "liquefaction" potential of the soils of hydraulically

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constructed earthen structures. Due to this event, the U.S. Army Corps of Engineers (USACE) began evaluating the seismic stability of its dams. Sardis Dam, a hydraulic fill dam, located in northwest Mississippi on the Little Tallahatchie River near the New Madrid Seismic Zone (an area responsible for three of the largest earthquakes in U.S. history in 1811 and 1812) was evaluated by USACE and found in need of seismic remediation. It is estimated that if the dam failed, in addition to loss of life, over 200,000 hectors (700,000 acres) would be flooded and total damages would be between $300 million to $1.2 billion (Stacy, 1994).

Sardis Dam has a total dam length of approximately 4,600 m (15,000 ft) and maximum height of 36 m (117 ft). The 2,600 m (8,500 ft) central portion of the dam, constructed by hydraulic filling, consists of a predominately silt core surrounded by a sand shell. The foundation consists of a 3 to 6 m (10 to 20 ft) thick layer of silt and clay (topstratum clay) extending approximately 370 m (1,200 ft) upstream of the dam. The topstratum clay is underlain by pervious alluvial dense sands (substratum sands). The topstratum clay was removed in the downstream area of the dam during construction of a seepage cutoff (Stacy, 1994).

The selected remedial treatment for Sardis Dam included construction of an 300 m (1,000 ft) upstream berm (completed in 1988 at a cost of $4.4 million) and the first known use of driven precast concrete piles for seismic remediation (initial contract price of $9.9 million) to strengthen an additional 825 m (2,700 ft) on the upstream slope of the dam; the cost per unit length of upstream remediation was lower for the pile reinforcement than for the berm reinforcement. The piles provide a reinforced zone across a weak layer of silty clay in the dam's foundation which is subject to significant loss of strength during a major seismic event. The piles are designed to transfer the static and dynamic loads in the dam into the higher strength sands below, thus preventing large lateral displacement of the upstream slope (Stacy, 1994). Due to the unique purpose of the piles of insuring the structural integrity of the dam and reservoir pool during a major earthquake, an extensive quality assurance program was implemented.

Probably the most important element of the quality assurance program was the dynamic monitoring of the piles during driving. Dynamic pile monitoring involves attaching sensors to the pile to measure the pile force and velocity. This data is used to then calculate 1) the energy delivered to the pile to investigate hammer performance, 2) driving stresses, 3) pile integrity, and 4) bearing capacity of the piles (Hannigan, 1990). While axial bearing capacity was not an issue in the pile design since pile loads at Sardis Dam are lateral, capacity during driving was important to the blow count and driveability. Therefore, a numerical CAPWAP analysis (Rausche, 1972; Hannigan, 1990) of the measured data was necessary to provide information on both static and damping behavior of the soil. Dynamic pile monitoring using the Pile Driving Analyzer was utilized in a downstream pile driving test program during pile design in 1991, a pile driving test program which involved the first few upstream production piles in 1994, and periodically during production pile driving.

Dynamic pile monitoring was also very beneficial in evaluating driving equipment, driving procedures, and cushion thicknesses. The monitoring of the tensile and compressive driving stresses in the piles was very important in verifying the unique design of the prestressed piles. To resist the large lateral loads during a major earthquake, the pile design also required regular reinforcing steel versus concrete ratio at maximum allowable limits. Pile dynamic monitoring and wave equation analysis information were valuable during several contract modifications involving changes in pile driving equipment and procedures. This paper gives an overview of the pile dynamic monitoring program at Sardis Dam.

Downstream Pile Test Program - 1991

The initial concern of driveability of the prestressed concrete piles was assessed by a pile driving test program performed in 1991 during the early phase of pile design. Although the real zone for remediation was located upstream of the dam in the reservoir pool area, the test program was performed in similar soils at a dry land site downstream of the dam to reduce cost. The test program included 610 mm (24-inch) square piles spaced at 3.7 m (12 ft) centers, 508 mm (20-inch) square piles at 3 m (10 ft) spacing, and 406 mm (16-inch) square piles at 2.4 m (8 ft) spacing. Sixteen piles of each type were driven in a cluster of four rows of four pile each to assess densification effects of driving.

A Delmag D46-32 open end diesel hammer with a manufacturer's rated energy of 148 kJ (107 kip-ft) was used to drive all test piles. The Delmag hammer proved it could drive the downstream test piles to the desired penetration, however, the measured energy transferred to the pile was typically 37 kJ (27 kip-ft). Average blow counts during the driving of the 610 mm piles were 130 to 200 blows per meter (40 to 60 blows per foot). Final blow counts of near refusal driving (300 to 620 blows per meter; 90 to 188 blows per foot) were encountered in the last 600 mm of driving when the piles and helmet were overdriven below ground surface. The required driving time was about 1.0 hour per 16.8 m (55 ft) pile.

Since the upstream production pile driving would require driving the piles to full penetration below lake bed in up to 10 m (35 ft) of water, the downstream test program included driving some piles with a steel follower. While the follower was a heavy H section with extra reinforcing, its dynamic impedance was only about one third the 610 mm pile impedance. The low follower to pile impedance ratio caused additional significant energy loss to the piles when the follower was used. Driving time increased to 1.5 hours per pile due to energy reduction and time required to handle the follower.

Sardis Foundation Contract

The contract for Sardis required driving of 2,594 piles in ten rows at 2.4 and 3.6 m (8 and 12 ft) centers as shown in Figure 1. The piles were highly reinforced and prestressed 610 mm (24 inch) solid square sections with lengths of 16.8 m, 18.3 m, or 19.8 m (55 ft, 60 ft, or 65 ft). Pile lengths were

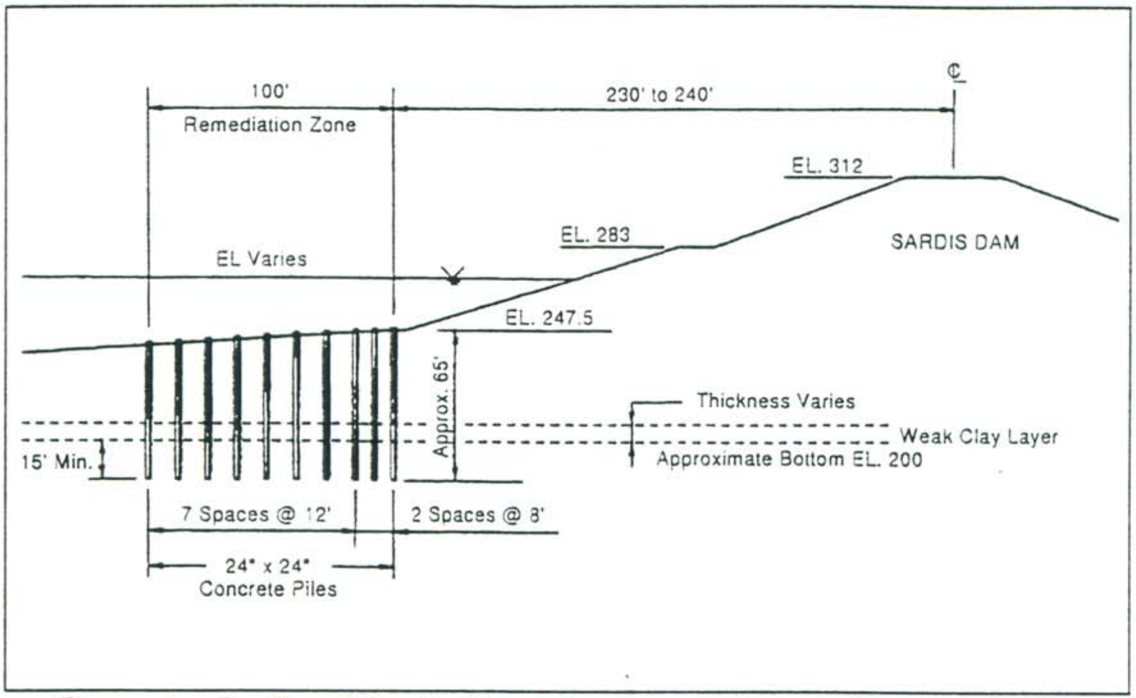

Figure 1: Profile of Sardis Dam showing upstream pile remediation

designed such that a minimum of 4.5 m (15 ft) penetration into the dense substratum sands was obtained for fixity of the pile. Because the area to be remediated was within the reservoir area which is also a recreation area for boats, piles were to be driven from a barge such that the pile top was flush with the lake bed. Due to the concerns of energy losses, follower performance during high impacts, pile driveability and productivity using a steel follower, and the effects of variable water depths and lake levels on driving procedures, the USACE prohibited the use of followers. An IHC S-90 hydrohammer was specified in the construction contract. Its underwater driving capability would remove concerns about variable lake levels and piles could be driven in one setup, thus increasing overall productivity. The S-90 has a 45 kN (9.9 kip) ram weight and a manufacturer's rated energy of 90 kJ (66 kip-ft). The contractor mobilized a fixed lead system for the S-90 to avoid the need of an installation template and thus speed spotting and overall productivity. Two identical systems were envisioned to drive the required number of piles in the allotted time.

Prior to production pile driving, an upstream test pile program was specified in the contract. Twelve (12) piles were tested to confirm pile driving procedures for the variable energy S-90 hammer, to verify pile cushion type and thickness, and to confirm the structural integrity of the unique pile design. Special transducers employed for the underwater dynamic pile monitoring worked flawlessly for all piles tested. Although the maximum water depth at Sardis was only about 11 m (35 ft), other special under water transducer designs (Harnar and Likins, 1996) have been developed for water depths of theoretically up to 1000 m (offshore oil platform installations) and have worked satisfactorily in 150 m (current maximum depth to which they have been subjected). Although initially the transducers were to be retrieved by divers, the cost of divers proved higher than the cost of the special transducers and thus they were later considered sacrificial for each pile tested.

Several problems occurred in the April 1994 test pile program. Pile dynamic monitoring revealed high dynamic quake values (Likins, 1983) and resulting unacceptably high tensile driving stresses, and the S-90 hammer energy output was therefore often reduced to keep tension stresses within limits. It was very difficult to maximize the energy output to increase productivity while limiting tension stresses and thus establish an easy to apply driving criteria. Approximately 3,000 blows per pile were necessary to drive each pile to full penetration. This high blow count required time consuming multiple cushion changes, and therefore the time to drive each pile was about 3 hours which was considered unacceptable for production driving. The high blow counts required changing the pile cushion after the pile top was below water, which proved to be very difficult, and half the pile tops driven by the S-90 sustained damage before reaching final elevation. Although the pile tops sustained damage, dynamic monitoring indicated that pile integrity of the shaft was not compromised. Since lateral loading requirements in the lower soils governed the design, the piles with damaged tops were still considered acceptable. After driving only five piles with the S-90, it was concluded that a hammer with a much heavier ram would be required to drive the piles to the required penetration. A larger hammer with under water driving capability was not readily available.

Finding an alternative driving procedure as quickly as possible was highly desirable to minimize the contractor delays, cost impact, and to complete the work in the scheduled time. Considerations included what alternative hammers and equipment were readily available to the contractor. The basic requirements were: 1) match the mobilized barge/crane lift capacity, 2) allow use of the fixed leads to at least position the piles without a template, and 3) significantly speed up the installation time per pile. Since time was critical, all parties worked together to promptly find an acceptable solution and the contract was modified to allow different pile driving equipment.

Sardis Contract Modification

To investigate the alternatives proposed by the contractor and the USACE, a numerical simulation using the wave equation method (GRLWEAP, 1995) was undertaken. The wave equation models the hammer system and pile utilizing a series of discrete masses and springs. The soil is modeled utilizing both static and dynamic parameters (the input parameters for the wave equation were determined from the CAPWAP analysis of the measured data). The ram is assigned an impact velocity. Working in small time steps using finite difference techniques, the entire system is kept in dynamic equilibrium, keeping track of stresses and displacements for each pile element with time. The final set per blow (inverse of blow count) of the pile is computed for an input soil capacity.

Both contractor and engineer consultant performed independent wave equation analyses. Various combinations of hammer types and sizes, and followers proposed by the USACE, the contractor, and consultants were investigated. Data on static resistance and dynamic soil response parameters obtained from the dynamic monitoring and CAPWAP analysis was critical in this effort. It was observed from blow counts and capacity indicated by the Pile Driving Analyzer that no capacity increase (set-up) was observed on any pile when driving was interrupted for any length of time in either the 1991 test program or the piles driven by the S-90.

A two hammer driving system was selected as most appropriate for the conditions encountered. Hammer operating requirements for both hammers were developed and specified based upon the results of previous dynamic monitoring and comparison to wave equation predictions. Both hammers were mobilized, and by mid May 1994 the first piles were driven and dynamically monitored to verify the extensive dynamic studies.

An HPSI hydraulic hammer with a 91 kN (20 kip) ram weight and a maximum rated energy of 111 kJ (80 kip-ft) was selected for initial setting and driving of the pile to an initial penetration of approximately 6 m (20 ft) to fix the pile in proper location (Figure 2). The HPSI hammer was light enough to utilize the existing fixed leads which were specially fabricated for the S-90 hammer. During this first driving stage, the capacity was low and the hammer was typically operated at less than full stroke. Energy delivered to the pile was typically 46 to 55 kJ (33 to 40 kip-ft). Due to the high ram weight and low impact velocity of the HPSI hammer, it was determined that a 150 mm (6 inch) plywood pile cushion satisfactorily limited the stresses.

After the initial drive by the HPSI hammer, a Conmaco 300E5 air hammer with a 136 kN (30 kip) ram weight and a 12 m (40 ft) long steel follower for underwater driving was utilized to drive the piles to final grade. The dynamic impedance of the follower was designed during the wave equation study to match the pile impedance and thus minimize energy losses. The contractor's follower design was modified to better withstand the high impact forces and fatigue considerations. The Conmaco was equipped with a dual position slide bar allowing for either a 900 mm (3 ft) stroke with 125 kJ (90 kip-ft) energy, or a 1525 mm (5 ft) stroke with 208 kJ (150 kip-ft) energy. Swinging leads were utilized for rapid maneuverability (could reach several piles without moving the barge). The 900 mm (3 ft) stroke was used until the pile penetrated through the soft soil zone. Previous dynamic monitoring demonstrated that, when switching to the full stroke, the energy transferred to the pile was about 83 to 97 kJ (60 -70 kip-ft). A 305 mm (12 inch) plywood cushion was determined from the dynamic measurements to satisfactorily limit driving stresses.

Production Pile Installation

Additional dynamic monitoring tests were conducted in August 1994 after the contractor had driven a significant number of piles. A 230 mm (9 inch)

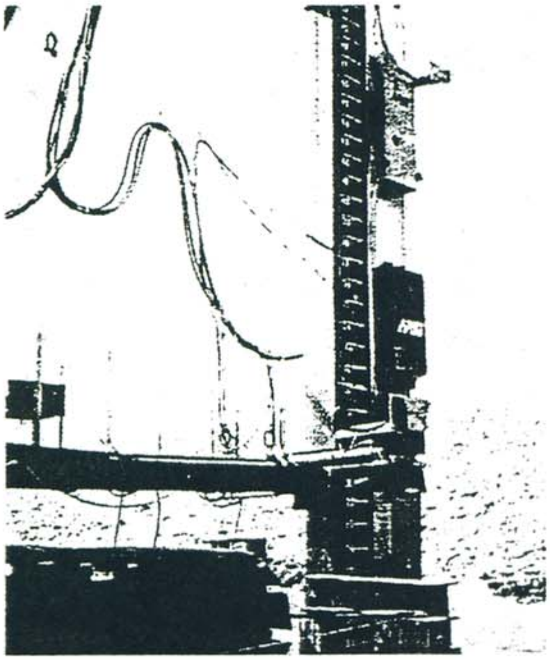

Figure 2a: HPSI driving concrete pile (on fixed lead)

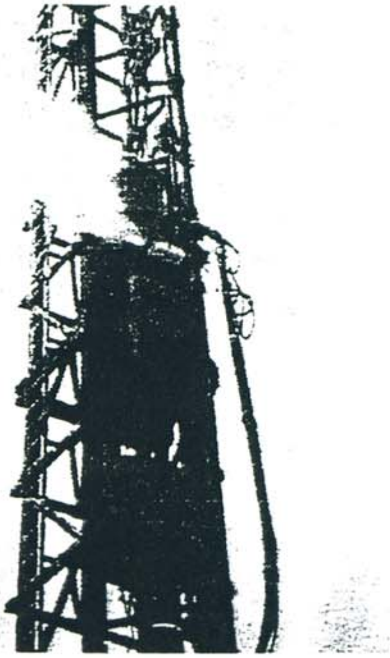

Figure 2b: Conmaco driving on the steel follower

plywood cushion was used with the HPSI hammer for up to three piles before replacement due to low blow counts. The HPSI hammer with fixed leads was very efficient in setting the pile in initial position without a template. The HPSI initially installed more piles than the Conmaco could in the same time period because of the initial difficulties with the follower design. Uninterrupted driving by the HPSI was critical to scheduling so as to not impact the contractors casting operation, therefore the HPSI operations were allowed to continue even though final driving to grade was interrupted. Thus, a three phase operation was established. First the HPSI would drive the pile about 6 m (20 ft). Although far behind the number of piles installed by the HPSI, the Conmaco (without follower) would next drive the pile to within about 900 mm (3 ft) of the water surface; the same 305 mm (12 inch) cushion would be used on typically three piles and the observed transferred energy at the full 1525 mm (5 ft) stroke was 103 to 114 kJ (74 to 82 kip-ft). Finally, using the full stroke, the redesigned follower, and a fresh 305 mm (12 inch) cushion for each pile, the Conmaco would drive these piles to final grade at a transferred energy of about 93 to 97 kJ (67 to 70 kip-ft). Some recommendations were made about the cushion exchange due to stress levels being slightly above desirable limits.

In November 1994, a final set of dynamic monitoring was performed. At that time the stage 1 driving with the HPSI was complete, and two different Conmaco hammers were being used (see Figure 3). One Conmaco drove the pile without follower to just above the water surface and the second Conmaco, with follower, drove the pile to final grade (see Figure 3). The contractor had by statistical comparison determined that blow counts and driving times had been increasing, and suggested this was due to overall

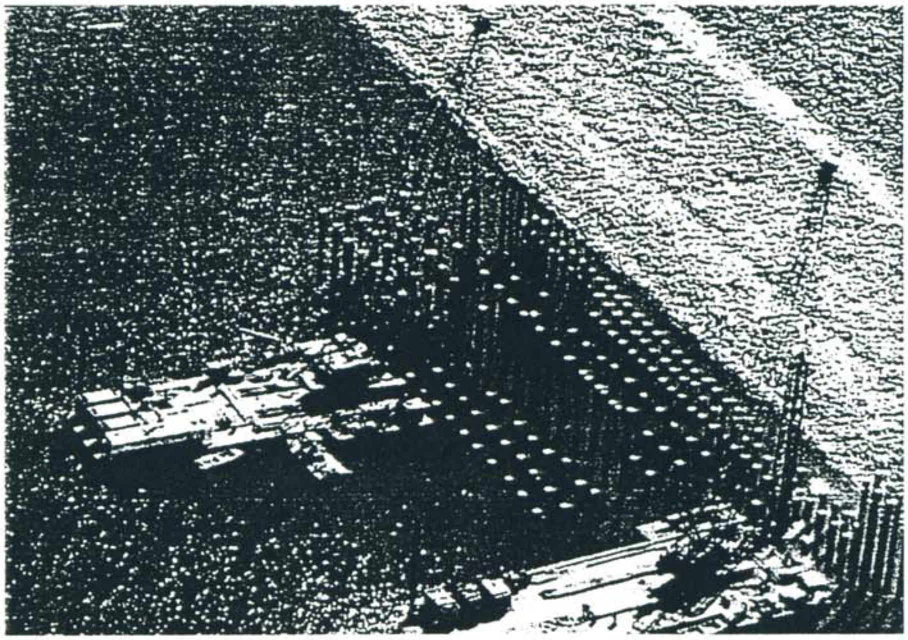

Figure 3: Two barges with Conmacos, Stage 2 (left) driving to water elevation, Stage 3 (right) driving to final grade with follower

site densification. However, the dynamic monitoring revealed that increased blow counts were due to decreased hammer performance. The Conmaco hammer at full stroke with follower for final driving to grade showed transferred energy was significantly reduced to only 65 to 83 kJ (47 to 60 kip-ft), compared to the energy transfer of 93 to 97 kJ (67 to 70 kip-ft) from the earlier tests. The contractor was advised of this situation and appropriate action was taken to restore normal efficiency and productivity.

The dynamically determined soil parameters from CAPWAP included relatively high Smith damping for the shaft (1.0 s/m; 0.3 s/ft) and a large toe quake (13 mm; 0.5 inch). The heavy ram and short stroke of the selected hammers was capable of overcoming these difficulties. Typically only 1,500 blows were required per pile. However, due to the three phase driving operation, the average time to drive a pile was about one hour. Stage 1 driving with the HPSI hammer was completed in early October 1994. Pile driving of all piles to final grade, interrupted several times due to low lake levels, was successfully completed in mid April 1995.

Due to changes in driving procedures from the initial contract, it became necessary to modify the contract which impacted the final project price. Wave equation studies again benefitted the project in projecting an approximate date, agreed to by all parties involved, when driving could have been expected to be completed had the S-90 hammer worked as projected. The final cost of the entire completed project is projected at approximately $13.5 million.