NYSDOT's Construction Control of Pile Foundations with Dynamic Pile Testing

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New York State Department of Transportation tests piles dynamically, and the results are used to determine final pile-driving criteria. Approximately 20 percent of projects having piles include dynamic testing. Although the majority of the tests are specified for in design, a number of dynamic tests are needed each year to solve construction problems. The dynamic test is used to verify predictions made using static analysis and the wave equation analyses. The intent of the pile program is to avoid and control pile construction problems. Dynamic testing is done on special projects that have peculiar or unique soil conditions, or when it is difficult to estimate soil parameters in design or in preconstruction analyses. Testing is also done on projects with soil conditions that are found to be different from those assumed in design and to troubleshoot pile-driving problems. Examples from field tests demonstrate how the testing program is used to check on concerns for pile capacity, pile length, and pile driving stress, as well as hammer operation.

New York State Department of Transportation (NYSDOT) uses four tools to estimate and verify pile resistance: the wave equation analysis of piles (WEAP) computer program, dynamic test, Case pile wave analysis program (CAPWAP), and occasionally a static test.

NYSDOT normally uses WEAP, dynamic test, and CAPWAP instead of the more traditional static test. There is a concern that the three methods are the same, implying a lack of redundancy in the program. The three methods are related, but by no means are they the same. They are all based on the principles of Newtonian physics, an analysis of instantaneous impacts. However, the problem of pile driving does not occur instantaneously. Therefore, any solution has to account for this fact and factor in a time of occurrence.

WEAP is a computer program that solves this problem by dividing the pile into a number of elements. It accounts for time by looking at each element of the pile. Soil parameters are applied to each element and combine with pile and hammer models to enable prediction of results. WEAP analyzes the effects of one segment on another during the short time interval it takes for a stress wave to travel through the pile segments. This program is normally used before driving any piles, to check on hammer and pile suitability to the anticipated driving conditions.

Dynamic testing, on the other hand, analyzes the pile as a whole, but not at the time of impact. The test is performed during pile driving. In essence, the test views the pile from the instant the stress wave begins at the top of the pile after the pile is hit by the hammer until after the wave completes its journey through the pile. Dynamic testing compares compression stress wave at impact and upon return to the pile head to determine what effect soil resistance forces have on the situation. This results in a capacity prediction. In this analysis, the time is an occurrence of the passage of a stress wave.

CAPWAP is a combination of the two previous procedures. By taking the data from the dynamic test and using it as input to a wave equation program, the user can compute, among other values, the capacity of the pile. This is accomplished by applying soil resistance, quakes (limits of static resistance), and damping constants (temporary dynamic forces). The end result is a prediction of capacity similar to that from a constant rate of penetration (CRP) static test. In fact, by applying increments of loads, a CRP plot can be computer-generated.

The static test is usually used only on large projects with high-capacity piles. These substructures rely on only a few high-capacity piles to support a large structure, resulting in a low redundancy factor. When the static load test is used, it is usually a CRP test method to failure.

PILE CONTROL

WEAP is used both during the design process and during construction. When piles are required because of possible scour, the piles must be driven into competent material, which usually necessitates hard driving. This has the potential for causing overstress of the pile, especially for cast-in-place (CIP) piles. Generally, the equipment the local contractors are apt to use is known. A hammer is assumed and a WEAP is run to check pile stresses. If an overstress problem is likely, a heavier pile section is required. The wall thickness or pile size is increased until a pile section is found that will not likely be overstressed. This type of analysis allows specifying the proper size pile in the bid documents. The other option, not as desirable, is to wait until the equipment is submitted for approval by the contractor and then find out that a heavier pile is required. This last situation often results in requiring an order-on-contract for a change in pile size.

WEAP also is used during design for concrete piles. An analysis is performed to check tensile and compressive stresses. This may result in specifying limits on hammer size or type or specifying certain thicknesses or kinds of pile cushions.

The most common and routine use of the wave equation is during the construction of a project. The state requires that

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the contractor submit his or her hammer-pile system for approval. Part of the approval process is the use of WEAP. It is used to check the ability of the hammer to drive the pile without overstress. A blow count is calculated for the inspector to use. In the case of diesel hammers, a means to determine that the hammer is working at the proper stroke is established. This could be either a blow rate (single acting hammers) or a bounce chamber pressure (double acting hammers). This procedure ensures that a minimum energy is used in driving the piles.

Again with concrete piles, the proposed pile cushion is checked. This is usually a requirement to limit tensile stresses, because a very minimum amount of cushion is necessary to guard against compression stresses.

Dynamic testing is used for a variety of reasons. It is used not only to determine capacity but also to monitor stresses, hammer performance through measurement of energy, and pile integrity and to determine lengths of existing embedded piles and sheeting. NYSDOT uses the pile driving analyzer made by Pile Dynamics Incorporated. The model of the analyzer currently used is GC, with many previous tests made using models EB from the mid-1970s and GA from the early 1980s.

A dynamic test begins by attaching strain transducers and accelerometers at the top of a pile by tapping in or bolting. Electric leads connect the instruments to the analyzer. The contractor then drives the pile with an impact hammer. Each blow creates stress waves that are picked up by the instruments and sent to the analyzer. The analyzer uses wave theory to evaluate the blow and show or print the results. The results, in part, can include resistance, energy transferred to the pile—as well as maximum and minimum forces—and velocities.

CAPWAP was developed as an adjunct to the Case Western Reserve piling program that produced the pile driving analyzer. This is an interactive computer program used to model the soil and how it acts on the pile. The digitized data from one blow from the dynamic test are input into the computer via a modem. This blow is then analyzed.

The majority of soils in New York State produced problems during dynamic testing. These problems are usually a result of dynamic resistances, or large toe quakes. Therefore, it is necessary to perform CAPWAP analysis on most of the dynamic test results. This ultimately allows a refinement of the damping parameter used during dynamic testing and results in improved confidence in the capacity predictions made during design.

CASE HISTORIES

To identify specific ways to use dynamic testing of piles in actual field situations a number of case histories are presented. The examples are situations or problems that presented themselves for interpretation and decision making. The cases are in four groups: pile capacity, pile stress, hammer energy problems, and existing piles.

Pile Capacity

Determining soil resistance is the primary reason for performing most dynamic tests. The capacity prediction cases have been divided into three groups, to show how

- Pile length can affect capacity (two cases),
- Setup is very evident in some soils (one case), and
- The dynamic test can allow a lower safety factor (two cases).

A project at Schroon Lake in the Adirondack Mountains shows how pile length affects pile capacity. A dynamic load test on the first estimated 50-ft-long, 35-ton CIP pile indicated capacity was reached in the medium dense sandy soil at 50 ft. As pile driving progressed on other piles, driving became harder and harder. A review of the driving records and the dynamic load tests indicated that, as driving progressed, piles began attaining capacity at 40 ft, and later on at 30 ft in some locations.

A static analysis shows that for each 1 degree increase in soil friction angle the pile should reach capacity 10 ft shorter. A 32-degree friction angle resulted in a 50-ft-long pile, 33 degrees in a 40-ft-long pile, and 34 degrees in a 30-ft-long pile. The conclusion is that the medium dense sand was becoming more dense from either the volume displaced by the CIP piles or the vibrations generated by pile driving, or both.

Another example of determining the required penetration is a procedure used on a bridge over the West Canada Creek. Here the profile consisted of 30 ft of medium compact silty sand underlain by 60 ft of soft lacustrine soil over a very compact till. Although the bearing capacity of the soil was sufficient to support a spread footing, piles were required to protect the structure against scour. However, it was not necessary to drive to the till layer if piles could be terminated in the silty sand layer. To accomplish this it was decided to use tapered monotube CIP piles. The final length was determined by dynamic test.

The piles were instrumented and monitored throughout the driving. As would be suspected, the resistance steadily increased. At about 5 ft short of estimated length the required capacity was achieved. The pile driving continued, and about 2 ft deeper the capacity peaked and began to drop off. This was to be expected as the pile began to lose tip capacity on entering the lacustrine layer. As it happened the desired capacity was achieved before the capacities peaked.

An example of determining setup is at a bridge over the Oswegatchie River. The foundation was to have 35-ton 12-in.-diameter CIP piles driven into a loose sandy silt soil. Pile lengths were estimated at 50 ft. WEAP indicated that 28 blows per ft (BPF) would result in an ultimate resistance of 140 kips. Two dynamic tests showed that the piles missed achieving capacity, with a capacity of 105 kips and a safety factor of 1.5 at a blow count of 10 BPF. Below a depth of 50 ft, the soil changed to a clayey silt. The capacity of the pile in this layer dropped to 60 kips. On reaching another sand layer 20 ft deeper, the capacity increased again. Piles were stopped at 50 ft, and another dynamic test was scheduled on a retap of the pile. Without a dynamic test, the pile would have been driven an additional 20 ft to reach blow count. Results of a dynamic test indicate that the required capacity was achieved.

With the dynamic testing results, confidence in pile capacity is greatly increased. Although NYSDOT's procedure calls for piles to be driven to a capacity of two times the allowable load, occasionally a lower safety factor is used in construction, because of this confidence. For the Mohawk Street Bridge over the New York State Barge Canal, 45-ft-long, 50-ton, 12-in.-diameter CIP piles were being driven into a silty sand with some clayey silt layers. WEAP results indicated a blow count of 77 BPF, corresponding to a capacity of 100 tons. The first pile was driven to 75 ft before reaching this blow count. The contractor was instructed to drive one pile to the estimated length with a dynamic test performed. The blow count at 45 ft was 20 BPF. The retap test at 45 ft showed that capacity was reached, with a first inch blow count of 6 blows per inch (BPI). This is close to the WEAP results. Therefore, all the piles were driven to 45 ft.

There were only 26 piles to be driven in this last substructure. By the time the dynamic test was performed, almost all the piles had been driven to the estimated length. By the next day, driving was done, and the piles were poured and capped soon after. A review of the dynamic test data in the office, however, turned up a problem. Due to operator error, incorrect transducer calibrations were used. This occurred with the old model EB analyzer, with which the oscilloscope cannot be directly used to visually check the incoming information. The result was that the true capacity of the piles was 75 tons, resulting in a safety factor of 1.5 on the allowable load. Interestingly, if the piles had been stopped at 38 ft, the blow counts were higher and the set-up capacity may have been better. The piles were accepted.

Now, with a recent model analyzer the incoming information is verified so this error should technically not occur again. All field results are also immediately reviewed, and operators now send in data from the field for main office reviews. The analysis is usually finished before the return of the field personnel from the field to the office.

Another example of accepting a lower safety factor is the Sunnyside Street Bridge. The soil was a 22- to 25-ft-thick layer of sand over a 75-ft soft clay layer. The static analysis showed that 35-ton, 12-in.-diameter CIP piles could be stopped in the top layer having mobilized a resistance equal to the allowable load with a safety factor of 2.0. The dynamic test, however, resulted in a safety factor of only 1.7. The only way to get a safety factor of 2 would be to drive the piles 95 ft long. A reduced safety factor was used which avoided a considerable added cost.

Pile Stress

Occasionally pile stress is of concern, particularly with short H-piles to rock, as well as all concrete and all timber piles. Often a dynamic test is required to check on pile stress as well as pile capacity. Pile stress is verified as a matter of course on all dynamic tests. Three cases are presented to show how

- Overstress can be controlled with testing,
- Through testing, pile damage can be identified, and
- Hoop stress can be monitored.

Dynamic testing was used primarily for overstress control at a project at the Waterloo Prison facility. There, 10 by 42 H-piles were intended for an allowable load of 45 tons being driven 13 ft to 30 ft to rock through a silty clay soil. It has been common practice in driving piles to rock to drive to 20 BPI, a general termination criterion. When the driving system is marginal, a minimal increase in capacity will result in a large blow count increase. This condition is accounted for by specifying a lower refusal criterion on a project-by-project basis. This criteria is based on the WEAP results.

On this project, two test piles were driven to a 20-BPI criterion. The first pile was 30 ft long and was driven to a capacity of 200 tons determined by the pile driving analyzer. This resulted in a maximum stress of 28 kips per square inch (ksi). The second pile was 15 ft long. It reached an ultimate capacity of 200 tons; but as a full 20 BPI was reached, overstress occurred and the top 1 ft of pile was damaged. The dynamic test indicated a stress of 45 ksi at a location 2 ft down from the top of the pile. A review of the dynamic test results showed that as long as the pile was driven only to 3 to 5 BPI, damaging the piles was unlikely, and the pile capacity increased minimally beyond that point. Of the production piles, the short piles were driven to the reduced blow count.

A project in New York City serves as an example of detecting pile damage. H-piles were required to penetrate through a bouldery till to rock. Most of the 70-ton-allowable-load 12 by 53 H-piles were driven to the estimated length of 50 ft and reached termination criteria. Low headroom required that only 24-ft sections of pile could be placed at a time, with subsequent sections spliced on. One pile showed an increasing penetration resistance up to 50 BPF at 50 ft. At that depth the blow count dropped off to 10 BPF. Driving was stopped at 103 ft, without reaching the required penetration resistance. The field personnel thought the pile may have dropped into a bedrock valley, which is possible in portions of New York City. Dynamic measurements indicated that the pile was damaged at the splice location 40 ft down from the head of the pile. A second pile went 74 ft before reaching termination criteria. It had a splice at 24 ft. The remaining piles reached termination criteria at 50 ft. Apparently the piles hit boulders on the way down and deflected enough not to reach the 50-ft depth of bedrock. Where is the tip of that 103-ft pile?

Another stress that has been identified is a hoop stress. It is monitored indirectly in concrete cylinder piles as a compressive stress. Hoop stresses come about from the radial component of the compressive stress acting outward from the pile wall. In order to monitor these stresses the allowable tensile stress permitted by the spiral reinforcing in the cylinder itself must be found. This varies with the pitch and diameter of the spiral wire. Once the allowable tensile stress is calculated, then an appropriate value of Poisson's ratio will translate that into an allowable compressive stress. This allowable compressive stress will be considerably less than that which is normally found in the literature for driving concrete piles. This stress is unique to hollow piles. However, it is reasonable to assume that the same circumstances may exist in square and octagonal piles, which have voids cast in them to reduce their weight. For square and octagonal piles, detection and monitoring become more difficult because the void does not exist at the top of the pile as with the cylinder. The cylinder usually exhibits longitudinal cracks at the top since this is the area of highest compressive stress. However, with the American Concrete Institute (ACI) standard precast prestressed piles with hollows, the stress picture becomes more complicated because of the nonuniform cross section. This complicates the compressive stresses, as well as where the cracks will appear. If it appears that hoop stresses may be a problem, it may be advisable to dynamically monitor the pile by attaching the instruments at the top of the void and below the solid cross sections.

Hammer Energy

Hammer problems occur more often than many engineers realize. A decrease in hammer energy can trick a blow count pragmatist into being convinced of a good pile capacity. A dynamic test gives a capacity of the pile and the energy delivered to the pile.

Dynamic tests work only when there is a sharp impact. A dynamic test was scheduled for the piles supporting a 90-ft-span bridge over Hemlock Creek. The 90-ft-long, 35-ton CIP piles were to be driven with a Link-Belt 440 diesel hammer into a 120+ ft deep lacustrine clay and silt deposit. The graphical traces of force and velocity indicated a large cushion effect, which showed that the force had a shaky rounded top and no peak at impact. The diesel hammer was preigniting, and although it was able to drive the piles, the dynamic load test results were meaningless.

Coincidentally, the blow count was a little higher than the wave equation predicted, indicating a good pile. In order to verify the pile capacity, the contractor was asked to change hammers. He willingly did, since he knew the hammer was not working well, and the retap with an air-steam hammer showed the pile did have capacity.

Existing Piles

In addition to the normal dynamic testing, NYSDOT has used the pile driving analyzer to determine the length of sheet piling in the ground. This was done on two occasions. The first was on a number of sheet-pile check dams in a stream in Erie County just south of Buffalo. The designers were concerned that the sheeting was not long enough to withstand any additional scour. The pile driving analyzer was used as an integrity testing device to measure the time of travel down the pile and back and thus determine the length of pile in the ground. Another case was in the Bronx, New York, where the NYSDOT was planning to install a new trestle next to an existing bulkhead. The question arose as to the depth of the sheet-pile bulkhead. This was a concern in making a decision as to whether to replace the bulkhead or whether, if it was left in place, it would interfere with inclined piles. In both cases the lengths were found to be adequate.

Another use of the analyzer has been in the testing of existing piles. Many of NYSDOT's larger, more recent projects have been in upgrading interchanges to handle larger traffic volumes and widening Interstate highways in urban areas. Both deal in improvements adjacent to existing structures. On occasion, this involves building directly over an existing foundation. Because piles are already present, it is occasionally proposed to reuse some of the existing piles in the foundation. However, in order to do this the capacity of the piles has to be verified. This situation has been present on two Interstate projects in Syracuse. The piles for these bridges were installed in the late 1950s. They were installed as mandrel-driven thin wall shells. The piles were installed to twice the blow count determined by the *Engineering News* formula. Therefore, they were driven to many times the required design load, with this very efficient driving system. All of the piles were driven into either a till soil or decomposed shale.

On one project the foundations were to be CIP piles, the same as the existing foundations. This required the existing piles to retain the hook bars for attachment to the reinforcing steel in the cap. Dynamic testing required straightening the hook bars and using a follower to drive the pile. The follower consisted of a piece of 3/8-in. wall pipe, with a splicing collar on the bottom. A plate was attached into the collar, fitted with holes to accommodate the straightened hook bars. Beneath the plate on the pile head was fitted a cushion of 3/4-in.-thick plywood. The pile-driving hammer for the redrive was the same one used for the project piles. This was a Link-Belt 440, a closed-end diesel hammer. This appeared to be a very reasonable driving system. However, as the test proceeded it became obvious that the hammer was not powerful enough to mobilize all of the soil resistance supporting the existing pile. On returning to the office, and examining the data further, it was found that a great part of the energy was in fact lost in the follower system, partially because the pile being redriven was so much stiffer than the follower.

Another project used H-piles as the foundation for the new structure. However, since the footprint of the new bridge foundation overlapped the existing foundation, it was decided to reuse some of the piles. The existing foundation was higher in elevation than the proposed foundation, therefore the hook bars could be eliminated.

With the hook bars cut off, the need for a follower was eliminated. The hammer for this project was a Link-Belt 520 closed-end diesel. However, since the existing piles were embedded in the decomposed shale it was difficult with that hammer to move the pile sufficiently to mobilize all of its capacity. The lower-bound prediction was, however, sufficient to indicate that the piles had a satisfactory capacity to be reused.

The lessons to be learned from these experiences are the following:

- There is a potential for the reuse of existing foundations when the opportunity arises.
- When testing existing piles, make it clear in the contract documents that a larger pile-driving hammer may be necessary for the redriving and testing of the existing piles. It may even be necessary to specify a minimum hammer energy for this purpose.
- If it is necessary to use a follower, it should be designed such that its impedance (AE/c) is as close to the existing pile being tested as possible. This also may have to be specified in the contract documents.

The way to avoid the use of the follower is to have the hook bars cut off and drill and grout new ones in after the test. The other option is to choose an existing pile that is not in the footprint of the new foundation and can be tested and abandoned. This last option is the game plan for an upcoming test to be performed in Utica.

SUMMARY

NYSDOT's intent is to avoid and control pile problems. The pile program has the same level of concern with the pile-driving stage as there is in the design stage. The dynamic test is used to verify capacity predictions made by the static analysis and the WEAP. The strength of the program is the continuity between design and construction. The designer designs the pile, runs the wave equation analysis, and goes out in the field to dynamically test the piles.

WEAP is used on all pile projects. Dynamic testing is done on special projects that have peculiar or unique soil conditions or when it is difficult to model soil parameters. Testing is also done on projects with field soil conditions different from those assumed in design and to troubleshoot pile driving problems.

The long-term objective is to be able to modify both computation stages, static design and the wave equation analysis, through the CAPWAP results, as a way of bettering the designs. Examination of some factors like H-pile tip bearing capacity in soil and correlating damping and quake values with soil parameters has begun. Using CAPWAP makes these studies practical.

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