Dynamic Pile Driving Analysis
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Final Report

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February 1995

Published by
Minnesota Department of Transportation
Office of Research Administration
200 Ford Building Mail Stop 330
117 University Avenue
St Paul Minnesota 55155
INTRODUCTION

The current method for monitoring pile driving on Minnesota Department of Transportation (Mn/DOT) construction projects uses the Engineering News Record (ENR) formula. This formula, first developed in 1893, uses an oversimplified model of the pile driving system to predict the pile capacity in the field. Since the beginning of this century, however, engineers have known that this formula neglects many complexities involved in the pile driving system including wave action, hammer energy loss, pile flexibility, and different soil resistance factors. Modified versions of the formula have attempted to compensate for these shortcomings by including empirical adjustments and large safety factors. However, the formula still has been proven very erratic in predicting pile capacities. According to numerous pile load tests, the real factor of the formula’s safety can be as low as 0.67 and as high as 20. This means that piles monitored with the ENR formula are most likely being driven deeper than required, which results in higher foundation costs. It also shows that the formula may potentially prove unsafe by allowing piles to be driven to shallower depths than required.

To provide Mn/DOT with high-quality, economical foundations, we proposed and received $70,000 for purchasing the Pile Driving Analyzer (PDA) through the Breakthrough Innovation Program. A sophisticated analog/digital device with high-computational speed, the PDA uses one-dimensional wave propagation theory to calculate the forces acting on the pile that resist penetration. The PDA gives the test engineer immediate soil resistance, pile or shaft stress, and hammer efficiency results during pile driving, restriking, or impact testing. More than two-thirds of state transportation departments use the PDA, currently in worldwide use on more than 2,500 projects each year. For this project, we planned to receive training on the PDA and use it to monitor pile driving on selected projects in hopes of incorporating this more modern method of measuring pile capacity into Mn/DOT’s pile driving program.
FIELD AND OFFICE EXPERIENCE WITH THE PDA

As of this report's publication, we received the PDA and completed training on the equipment uses. The training consisted of five full days in the office and one day in the field. Attendees consisted of members of the Foundations Unit and the Bridge Construction Section along with representatives from the Federal Highway Administration (FHWA).

The office training consisted of learning the basic operation of the PDA and extensive training with its associated software, PDA PLOT and CAPWAP. We learned how to review the field data and print output files and graphs. We also spent many hours learning how to match waves with the CAPWAP program. This program allows the user to match a computer generated force-velocity wave for an individual hammer blow monitored in the field by adjusting soil resistance, damping, and quake factors. This iterative process, which solves a complex differential equation, allows the engineer to pinpoint the actual soil-pile interaction parameters at the site and to adjust the bearing capacities accordingly. Static Load Test studies corroborate the high accuracy of bearing capacities measured with the PDA and adjusted with the CAPWAP program.

The field demonstration took place in Shakopee, Minnesota on July 19 near the intersection of T.H. 101 and Scott County 18 on Bridge No. 70524. The PDA was used on Test Pile #2 on the West Abutment. The foundation pile for the bridge consisted of a 12-3/4" steel pipe pile with a 1/4" wall thickness rolled from Grade 2 steel (35 ksi yield strength). The piles were designed to safely carry 58 tons per pile but were to be driven to twice that capacity to account for a safety factor of two. Due to overhead power lines, the contractor was forced to drive and splice the pile we tested in 30-foot sections. After consulting with the pile driving inspector and the project engineer, we learned that the contractor had experienced some difficult driving at the site resulting in some piles damaged. They showed us a pile that had been installed earlier that was partially full of water. This usually indicates that the pile had cracked during the pile driving operation and groundwater had seeped into the closed-end steel pipe pile.
When we arrived at the site, the contractor had already installed the first of three pile sections for Test Pile #2. He told us that the first section was driven to a depth of 32 feet. We set up for testing the second and third pile sections by first drilling and tapping holes for two transducers and two accelerometers on the two remaining 30 foot pile sections. We then started the PDA software and entered the project information. Next, the contractor raised the pile and placed it in the crane leads. A member of the contractor's crew then climbed up the crane leads and attached the transducers and accelerometers to the pile. After running some final diagnostic tests, we set the PDA to its monitoring mode and signaled the contractor to begin driving pile. The contractor drove the second pile section to its total length of 30 feet. We next reset the PDA while the contractor spliced on the third pile section. After attaching the transducers and accelerometers, the contractor drove this third pile section approximately 16 feet and was told to stop the pile driving operation by the pile driving inspector. The inspector informed us that the pile was sufficiently deep to meet the specifications of Mn/DOT's pile driving formula. He explained that the pile was driven to a total depth of 78 feet below ground with a final blow count of 48 blows per foot or 1/4" per blow.
We set the PDA to its monitoring mode and signaled the contractor to begin driving pile.
During driving of the third pile section, the PDA displayed ultimate capacities of up to 380 kips or 190 tons. In addition, the PDA computed maximum compressive stresses in excess of 45 ksi occurring in the pile during pile driving. This concerned us because the pile was only designed to handle stresses up to 35 ksi. At the end of driving, the PDA showed an ultimate bearing capacity of 372 kips or 186 tons for the pile. The table below shows the results of the PDA test and Mn/DOT’s dynamic formula approach for determining bearing capacities.

<table>
<thead>
<tr>
<th>Ultimate bearing capacity at end of driving</th>
<th>Mn/DOT dynamic formula</th>
<th>PDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>118 tons</td>
<td>186 tons</td>
<td></td>
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Our field demonstration showed that Mn/DOT’s dynamic formula for determining pile capacities may be overly conservative on this specific site. With exclusive use of the PDA on this project, the number of piles needed could have been reduced from 85 to 58 piles per substructure. This represents a potential savings of approximately $28,000 for this substructure (70-foot average pile length x (85-58) piles x $15 per foot of pile). In addition, the PDA showed that the pile being tested experienced excessive compressive stresses. While the pile we tested did not appear to break (we did not internally inspect the pile), others in the same substructure were damaged and could not be used to support the bridge. If we had used the PDA exclusively on this project, we could have determined the reason for the difficult driving and made corrections to the pile driving system at the very beginning. This in turn may have saved additional costs on the project by eliminating the need to replace broken or damaged piles.
CONCLUSIONS & RECOMMENDATIONS

Overall we learned that the PDA is a fairly easy-to-use nondestructive testing device that can reliably predict bearing capacities of piles as they are being driven and also on pile re-strikes, piles that are redriven after the soils are allowed to settle. This sophisticated piece of equipment and its associated software also can measure pile driving hammer efficiencies, detect damage to piles, and measure soil/pile interaction parameters.

The PDA will save Mn/DOT money on bridge projects by:

- allowing engineers to safely decrease pile lengths
- allowing increased pile loads that will decrease the number of piles needed
- decreasing contractor claims by accurately measuring and documenting the pile driving system.

The amount of money saved on each project depends on site specific conditions such as different pile and hammer types and soil conditions.

Next, we plan to become more proficient at using the PDA and applying it to Mn/DOT projects. This summer we plan to test the PDA on more projects. After gaining the necessary experience with the PDA in the field and in the office, we will recommend and use the PDA on one or two selected projects each construction season. We would like to see the PDA used on many more projects, but, with limited personnel and only one PDA unit we have limited opportunities. During the recent biannual budget, we requested a full-time Senior Engineer Position to run the PDA. Eventually we recommend incorporating the PDA into Mn/DOT’s regular pile driving monitoring procedures.