Spatial Inspection of Steel Pile Driving Operations using Laser Scan Data

Chris Gordon, Ph.D. and Kerry T. Slattery, Ph.D., P.E.
Southern Illinois University Edwardsville
Edwardsville, Illinois

Pile driving operations present unique working conditions for the inspector. Piles are only visible during construction; part of their load-bearing behavior is inferred by their behavior during construction; and the equipment required to drive them into place is expensive, and introduces noise, vibration, and various spatial constraints to its environment. The inspector working in this environment must track numerous pieces of information before, during, and after the pile driving operation, to assess the load-bearing capacity of the piles and to establish the pay quantities for the pile driving operation. In the case of unexpected conditions (e.g. additional splices or piles required), the inspector must quickly gather numerous pieces of information related to the unexpected conditions and the possible claim for additional expenses. Laser scanners may be used to assist the inspector during routine inspection of pile driving operations. This paper describes the spatial information used to evaluate different phases of steel pile driving operations and presents data collected during a recent pile driving operation to demonstrate information that can be obtained to support pile driving inspections. Furthermore, the paper defines unique considerations related to pile driving operations that must be addressed to properly prepare for data collection and analysis using laser scanners.

Key Words: laser scanning, LIDAR, pile driving, inspection

Introduction

Researchers and practitioners are devoting recent attention to a concept of "intelligent pile driving" that incorporates feedback about sensor readings of properties (e.g. impact velocity, sound, and vibration) into pile driving operations (e.g. to adjust hammer throttle). The sensor readings that have been incorporated into these systems so far are not directly related to spatial data. However, inspectors and contractors collect a vast amount of spatial data for any given pile driving operation, and must do so quickly, and in great detail. Spatial data (e.g. pile length, facility settlement, and distance to hazards), is one type of data that inspectors must collect for load-bearing assessment, recording pay quantities, and documentation of unanticipated conditions. Hence, there is considerable opportunity to incorporate real-time spatial data collection, analysis, and feedback as part of an "intelligent" pile driving operation. Inspection of pile driving operations to evaluate quality and pay quantities occurs in unique working conditions: the piles are hidden to the eye after construction; the behavior of the piles during construction informs their load-bearing capability; and hence, inspectors must inspect in parallel with a construction process that introduces noise, vibration, and equipment-related hazards to its environment. Inspectors of this process must often act quickly to avoid holding up the entire operation, and keeping expensive equipment idle. Piles are driven amidst uncertainly about subsoil conditions, and hence, inspectors must quickly gather data about jobsite conditions if they are not as expected. The rapidity and detail with which inspectors must collect this data motivates the investigation of the applicability of laser scanners for use in this unique inspection application. As part of an on-going research study into construction applications of laser scanning for state Department of Transportation (DOT) construction, we have monitored a pile driving operation for a recent bridge construction project using a Trimble GS-200 laser scanner. We survey the range of spatial information required of steel H-pile driving operations and evaluate whether the collected data can support these types of assessment. Furthermore, we document the unique requirements imposed by pile driving operations as one prepares to monitor pile driving using a laser scanner.

Pile Driving Overview

Piles are a type of deep foundation system that are employed either to support the superstructure of a facility through direct contact with soil or bedrock below or through friction with surrounding soil. Piles are generally driven into the ground from above, using pile driving equipment that drives a given pile into the ground with a series of blows generated by gravity-based or mechanical force. Piles are driven in this manner, on the order of feet, inches, or fractions of inches at a time, in the range of 30-60 blows per minute. When the design length is greater than the length of an individual pile, contractors splice two lengths together, often after driving the first length to near full depth. Prior to driving the set of piles for the foundation system, contractors employ the selected equipment to drive a test pile on the site. This tests the effectiveness of the equipment and selected pile type and cross-section by driving it deeper into the ground than designed and with greater energy than required by design. If the test pile confirms these intended aspects of the operation, the contractor continues with full-scale production according to the plans and specifications.

Inspectors must quickly make assessment of pile quality and integrity, and notify the contractor if the pile has sufficient load-bearing capacity, or is damaged or in conflict with specifications (e.g. is out of plumb or batter or is installed in the wrong location). Inspectors cannot "inspect quality in" to a foundation system, but can provide feedback to the contractor during the pile driving operation while it is still possible to correct problems encountered during pile driving (or to stop the contractor as soon the pile reaches required bearing capacity and before the contractor expends any additional amount of resources). Inspectors might not be familiar with the particular specifications for a given project, so any assistance that can be provided in automating the inspection process can free the inspector to provide rapid feedback about a pile driving operation. Many pieces of information that assist inspectors in inspecting pile driving operations have visual components. Hence, one way to support inspectors is to rapidly and comprehensively collect and analyze spatial data about pile driving operations.

Laser scanners provide an example of such a tool that can be employed to rapidly and comprehensively gather spatial data about pile driving operations. Laser scanners are capable of rapidly collecting highly accurate and detailed spatial data within a range of hundreds of meters. Laser scanners gather several thousands of points in 3D space within line of sight of the scanner. Each point consists of x, y, z coordinates, and often additional data, such as color and intensity readings. Depending on the scanning technology and scanner settings, scanners collect data at thousands of points per second. A complete 360 degree scan takes on the order of minutes to complete using a typical laser scanner. One can feasibly limit the scan area and resolution (e.g.

spacing of point measurements) to a small portion of a given pile in order to more quickly assess pile geometry. However, manually operating a scanner still results in a slower frequency of data collection (e.g. on the order of minutes per scan) than the 30 to 60 blows per minute of a pile driver (and hence the rate that the pile changes location). This speed of data collection does, however, enable one to gather data at points in time when contractors are not actively driving piles. Using this data, an inspector can judge the current state of a pile, as well as the difference between scans collected at different times (e.g. to interpolate between two states). Additionally, one can use additional data collected by a laser scanner (e.g. ground surface conditions) in other analyses, such as calculating pay quantities for earthwork. The Construction Department at Southern Illinois University – Edwardsville has obtained one such scanner (a Trimble GS200), and is studying the applications of this technology for construction applications, particularly those related to DOT scopes of work.

Survey of Building Codes and Specifications

We reviewed the standard specifications and building codes of selected DOTs as well as cities, agencies, and industry organizations to gauge the range of spatial information important to this domain. Naturally, standard specifications may be modified to address unique requirements of specific projects. However, standard specifications (as well as codes and specifications from other organizations) provide a basis of understanding of the general concepts important to pile driving in each state surveyed in this manner. Examples of spatial information that is required or can be gleaned are pile geometry, pile placement and orientation, installation sequence, length of pile furnished and kept in place, and pile behavior after pile driving. These different types of information span a typical pile driving operation from before, during, and after a contractor drives any given pile, and vary in terms of the amount of detail required.

Data Collection Prior to Pile Driving

Prior to installation, inspectors must verify that the furnished piles have the correct dimensions (this applies to piles driven as test piles and piles driven thereafter). The Construction Engineering Research Laboratory (CERL) pile driving study "Inspection of Pile Driving Operations" notes that submittal data should include pile cross-section and delivered length (Davisson, 1972). The "Installation Specification for Driven Piles" (an industry specification modeled on American Association of State Highway and Transportation Officials (AASHTO) Driven Pile Installation Specification), notes that the cross section of rolled steel piles must be H or W shape (PDCA 2007). Furthermore, the specification details the dimensions for the flange and web independently and relative to each other. Hence, inspection of the piles prior to installation requires measurement of the individual dimensions of pile cross-section and delivered length; these in turn can support further analyses (for example verifying that the flange width is not less than 80% of the section depth, in accordance with the Pile Driving Contractors Association (PDCA) specification).

Data Collection During and After Pile Driving

During a pile driving operation, the contractor may drive test piles (or probe piles); then drive the remainder of piles; then re-drive, remove, add, or modify piles as necessary if they experience any difficulty in driving any of the piles. Contractors may re-drive piles in the case of pile heave, for example, where the surrounding soil causes a pile to displace after it is driven. In the case of damage, contractors may remove or add additional piles. If the pile has not reached sufficient bearing capacity, contractors may splice additional lengths to the pile and drive the additional length into place. Inspectors and contractors must quickly make assessments about whether or not piles address specifications related a variety of properties, such as embedment depth, damage, and alignment. Examples of the range of spatial data required follow in the upcoming paragraphs.

Inspectors and contractors may visually assess the process- and product-related requirements of specifications during construction. For example, one commonly specified process-related requirement is the order of pile driving in a pile group. Alabama DOT, for example, requires that contractors start in the center of a pile group and work outwards in each direction (ALDOT 2000). PDCA recommends either this method or starting at one end of the group and working across the group in one direction (PDCA 2007). In addition to process-related specifications, numerous product-related specifications require accurate placement of piles for structural- and pay-related purposes.

Numerous codes and specifications require inspection of pile location relative to design location. For example, New York City Building Code (New York City 2004) and Alabama DOT (ALDOT 2000) require that pile location be within 3 inches of plan. Bay Area Rapid Transit (BART) specifications require tolerances for pile tops to be within 6 inches (BART 2004). PDCA notes that tolerances any tighter than 3 inches are impractical (PDCA 2007). Location of piles with respect to plan is not the only important reason to measure pile location. This information is also used to gauge the effect of pile driving on other construction tasks. For example, BART specifications require that piles cannot be driven within 20 feet of concrete that is less than a week old, to prevent vibration introduced by pile driving from causing segregation within freshly placed concrete (BART 2004). Additionally, numerous specifications institute minimum spacing between piles. New York City Building Code, for example, requires a minimum spacing of 24 inches, and a pile spacing of 1.75 times the diagonal distance of rectangular piles (New York City 2004).

In addition to location information, common requirements for spatial measurement are measurements of pile length in place. Pile length measurement is important not only as a pay quantity, but also as an inspection item. In the event that required pile length exceeds the length of a given section, piles may be spliced to additional lengths. These lengths must be recorded, not only for pay quantities, but also to address any limitations on spices. Alabama DOT, for example, limits the number of splices to two. In the event that the length of a given pile segment is longer than necessary, it must be cut to the required length (ALDOT 2000). Typically, the contractor is not paid for material beyond the cutoff elevation, unless the contractor is paid a unit price per pile (not per linear foot). An important piece of spatial information that changes rapidly is the distance per blow of the pile driver. Inspectors track the number of blows per inch

to estimate the bearing capacity of the pile. This information is particularly used when the pile reaches a state of practical refusal. PDCA, for example, requires that pile driving should not exceed 3 inches at a state of practical refusal (e.g. 5 blows per 0.5 inch) (PDCA 2007).
In addition to pile length and location, pile orientation and condition is a final set of spatial information to be collected during construction. Regardless of whether a pile is installed vertically or at an angle, piles are allowed a limited amount of eccentricity to be assumed to have their designed behavior. For example, New York City Building Code allows tolerances for plumb or batter to be 4% of pile length based upon a minimum of 2 feet exposed section of installed pile (New York City 2004). Piles that are bent during installation face the same tolerances. BART specifications allow tolerances for plumb or batter to be 1/4 inch per foot of pile length, not to exceed 6 inches overall (BART 2004). PDCA specifies tolerances of ¼ inch per foot for plumb and ½ inch per foot for batter (PDCA 2007). In addition to evaluating tolerances for plumb and batter (in the case of intact or bent piles), inspectors must determine whether piles are intact. For example, BART specifications require that piles be rejected if they exhibit defects, such as cracks, bows, or chips (BART 2004).

Lastly, depending upon the soil type, driven piles may displace after being driven, a phenomenon known as pile heave. Depending upon how much the piles heave, they may need to be re-driven. For example, in one portion of the Central Artery project in Boston, 68% of the piles had to be re-driven at least once due to pile heave, and a smaller percentage twice (FHWA 2006). Pile heave requirements for the selected standards and specifications are largely similar. PDCA (PDCA 2007) and the Massachusetts Building Code (Massachusetts 2005) require re-driving piles for heave of more than 0.5 inch, while New York Building Code (New York City 2004) and Alabama DOT (ALDOT 2000) require re-driving for heave greater than 0.25 inch.

Additional Spatial Data Required During the Pile Driving Operation

In addition to monitoring piles in different levels of detail through each phase of a pile driving operation, an inspector can glean spatial information about a pile driving operation with respect to its environment. In particular, inspectors can reason with spatial information about distances to nearby objects to determine if the pile driving operation poses a threat to the nearby object, or vice versa. In addition, the inspector can gather spatial information about these objects during construction to determine if they are at all changed during the pile driving operation.

The height of piles (and hence the rigs needed to raise and drive them) is on the same order of magnitude as power line heights. Hence, pile driver operators must observe a safe distance between the pile driver and nearby active power lines. Occupational Safety and Health Administration (OSHA) Standard 1926.550, for example, places the minimum distance between any part of the load and crane and active power lines rated 50kV or below to be 10 feet (OSHA 1998).

Specifications typically indicate that customized monitoring procedures be established if structures are near a pile driving operation. In this case, information about the location of particular facilities before, during, and after pile driving can identify if any settlement has occurred as a result of the pile driving operation. For example, New York City Building Code requires monitoring at-risk neighboring structures at 24-hour intervals to determine if they move during operations such as pile driving (New York City 2004).

Data Collection During Pile Driving Operation

To gain initial insights into laser scanning support of pile driving assessment, we collected numerous scans during a recent pile driving operation. We collected data at three basic stages of the overall operation: prior to pile driving; during splicing of piles; and after completion of pile driving. To avoid interaction with the construction operations, we maintained one scanner setup overlooking the operation. To ensure that we maintained control over time, we repeatedly scanned registration targets between scans of the construction site. Normally, this is done to align scans from different locations. However, given that pile driving can cause settlement in the soil surrounding the pile driving operation, we employed this approach to ensure that we maintained control over time.

From the scan data obtained we were able to make numerous measurements outlined above: width and depth of cross-section; length of pile from splice point at bottom to top of the pile; cut-off length; pile installation sequence; distance between piles; distance between pile driver and nearby concrete operations; and distance between crane and nearby power line (see Figures 1 and 2). Additionally, from this data, we were able to compare nearby structure locations before and after pile driving.

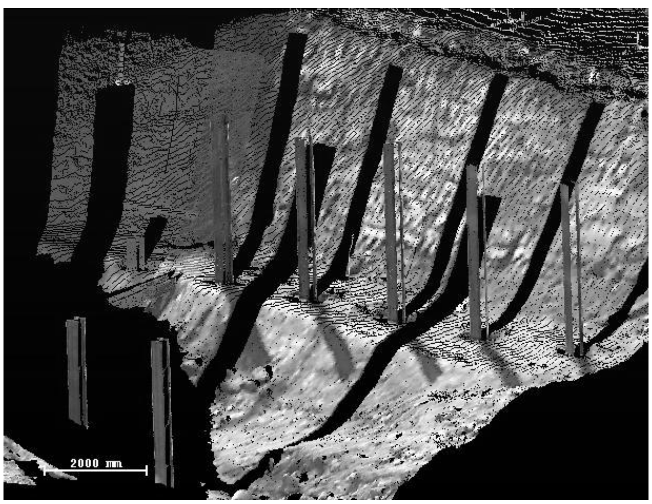

Figure 1. Scan of test pile and first lengths of pile shown, supporting measurements of pile location and geometry

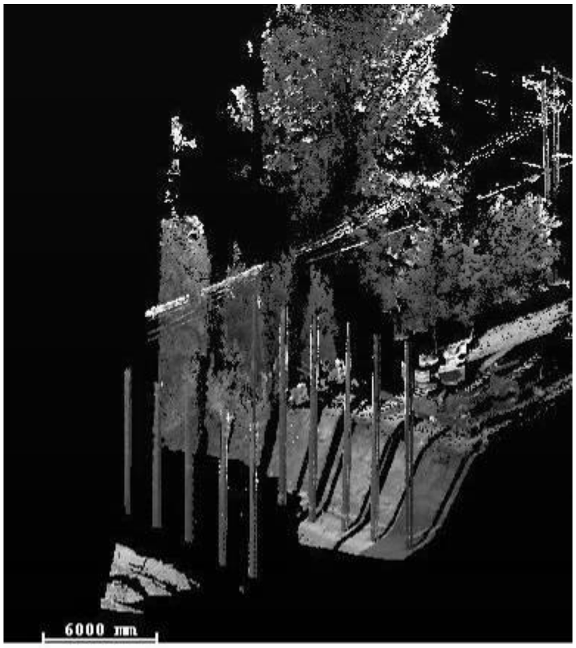

Figure 2. Scan data of active power line permits measurement of distance between line and crane

From the scanner's single vantage point, we were not able to collect sufficient data to make accurate measurements of web thickness (this would have been possible at a closer distance), nor were we able to collect data from multiple locations, from which to gain a more complete view of each pile. Due to the scanner's frequency of data collection (which is slower than the frequency of pile driver blows), we were not able to monitor the depth of pile embedment with each blow; rather, we measured the location before and after each length of pile driving.

Data Collection Process Observations

Establishing control and maintaining control is a challenge in normal scanning operations. However, given that the pile driving operation introduces possible settlement in its vicinity, this introduces additional concerns about the means and frequency of maintaining control in a series of scans. We addressed this concern by frequently measuring known points, sighting on distant landmarks (not expected to settle), and placing the scanner itself several yards away from the pile driver.

The speed of data collection is another factor that limited our data collection. While the speed of data collection was comparable to the speed of aligning and splicing subsequent piles, it was not comparable to actual driving of piles. Hence, measurement of blow counts per inch is not a good application of this particular laser scanning technology. However, much of the remainder of the operation proceeded at a rate comparable to that of the laser scanner, and hence this particular technology is applicable to inspections requiring detailed spatial data collection pre- and post-pile driving.

Unique Planning Considerations Related to Scanning Pile Driving Operations

Within a general framework for model-based inspection (Akinci, et al. 2006), researchers, such as (Latimer, et al. 2004) have begun developing scan planning algorithms to assist inspectors in determining where to locate a scanner for a particular scanning objective or set of objectives. Such algorithms consider sensor-specific information, such as the distance, accuracy, and field of view of the scanner; and the fixed location of the objects to measure (e.g. the designed location for the object); and try to identify possible locations and optimal paths for scanners to collect data. Pile driving presents a unique scan planning scenario, because the location of the object to scan is only visible when it is not fixed in place; in addition, the effect of the pile driver on control (due to potential settlement) and safety (due to the equipment, material, and energy involved) imposes a minimum radius that the scanner should maintain relative to the pile driver. As shown through our initial data collection, a large amount of relevant data may be collected when tied to the pile driving process (e.g. before pile driving, after splicing, and after cut-off). Hence, scan planning for pile driving operations, whether manual or automated, needs to be carefully linked to the installation process and the expected spatial configuration of the pile driving operation. The scanning process itself needs careful planning to ensure that control is maintained throughout the operation, and that scanning times are on par with installation times. In addition, to monitor the effect of pile driving on the environment (and vice versa), scan planning needs to consider the location of nearby structures that are at risk of settlement, nearby concurrent concrete placements, and nearby active power lines, as well as plans for data collection in adverse weather conditions.

Conclusions

Pile driving demands rapid feedback about numerous types of data, among them several types of spatial data. This feedback helps inspectors determine quality and pay quantities for the pile driving operation. Inspectors must rapidly gather a vast amount of data to avoid holding up active construction operations, and hence, can benefit from the rapid data collection support provided by laser scanners. To more fully develop the concept of an intelligent pile driving operation, inspectors need not only real-time spatial data collection, but development of automated reasoning and feedback mechanisms to incorporate this data into on-site work processes. The examples from building codes and standard specifications mentioned in this paper demonstrate the range and detail of spatial information required. In large part, we were able to gather the information required by these specifications using a Trimble GS-200 laser scanner on a recent pile driving project and manual analysis of the collected data. However, the case study demonstrates the additional planning and process steps needed to prepare for upcoming data collections related to pile driving. In particular, this case study exhibits a unique planning scenario that requires further algorithmic support to help inspectors locate their scanners and control points with respect to the pile driver and adjacent construction activity. Further research is needed as well in automating the analysis of this data to permit real-time assessment of on-site conditions, as warranted. For example, we have identified numerous measurements related to the pile driving product and process, as well as measurements relating a pile driving operation to objects and processes in the vicinity. While this initial data collection indicates that collection and analysis of spatial information using laser scanners is feasible during pile driving operations, further research in intelligent pile driving requires incorporation of planning support that relates the location of a scanner to a given pile and its environment; processes for collecting and verifying the accuracy of data; and automated reasoning to interpret spatial data in real time to support inspectors of pile driving operations on site.

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