The Economic Advantages of Dynamically Monitoring Driven Pile

A [dynamically monitored] driven pile is a tested pile

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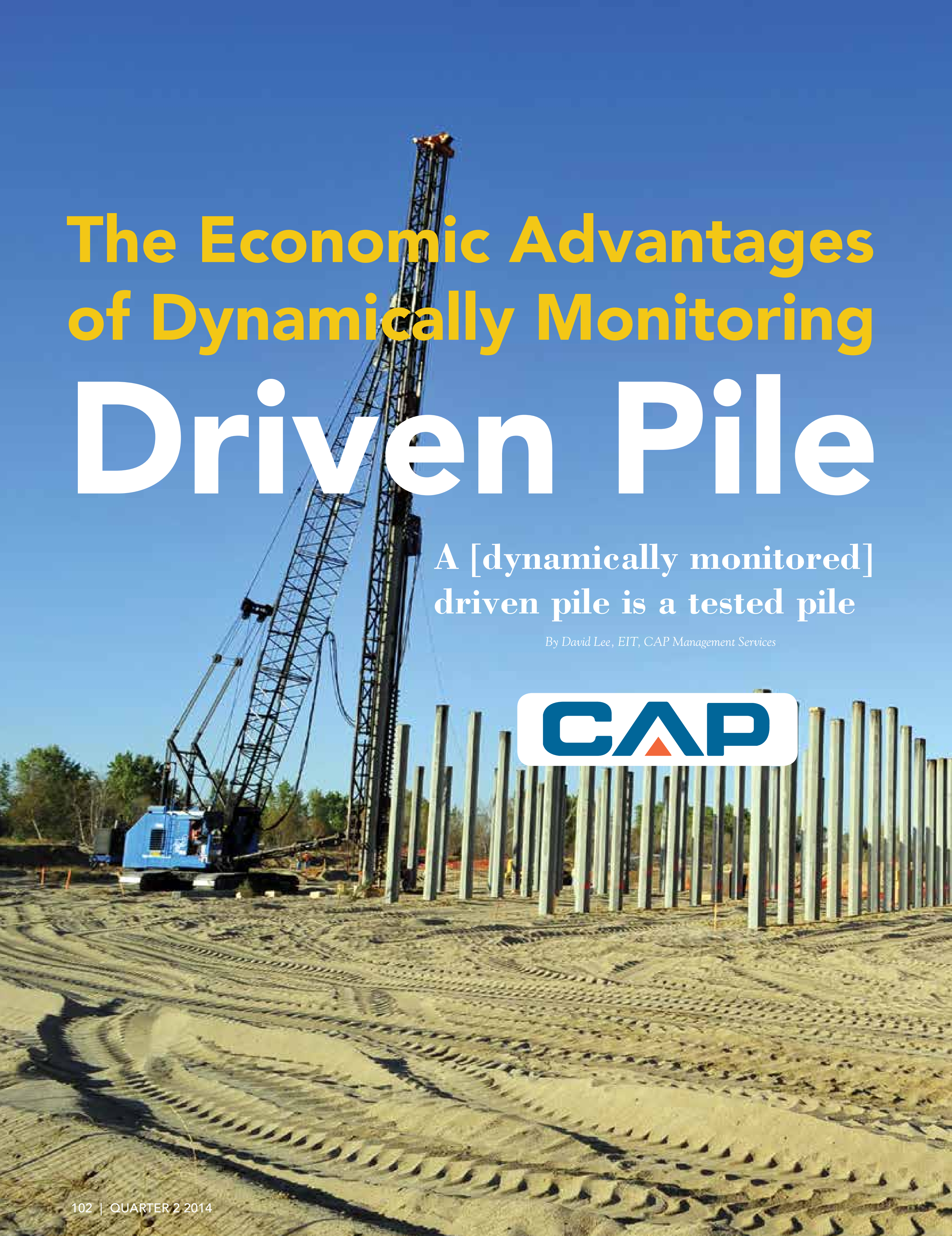

This article will illustrate how dynamic monitoring can be used to reduce the cost of driven pile foundations, which are governed by uplift capacity in comparison to relying on conventional formulas and blow counts. The information gained by dynamic monitoring is generally only replaced by static load testing, which due to associated high cost, logistics and schedule delays, is commonly not carried out. As a result, engineers tend to lean toward a more conservative design.

The introduction of dynamic monitoring can be related to when doctors were first able to use x-rays to look into the human body; engineers can now view and interrupt measured results of the location and magnitude of soil resistances along a pile's length and possibly improve the economics of the design while maintaining integrity. To support this argument, this article will use the findings of a transmission line project in East Central Alberta, Canada. Furthermore, the basics of dynamic monitoring will be described, and demonstrate how the results obtained can shorten required pile lengths and reduce the number of required piles, while maintaining a quality control process that engineers and construction personnel can use to evaluate the field results against the design specifications and capacities. The pile driving community will state that a driven pile is a tested pile; for economic and sustainable reasons this article hopes to demonstrate that when uplift forces govern the design, only a dynamically monitored pile is a tested pile. Many designs require the need to resist uplift forces and this extends to a variety of situations. Forces from wind heaving, frost heaving, expansive soils and overturning moments lead to design that must resist uplift forces and when this is the case, owners, contractors and designers should not rely solely on blow counts.

Wave equation

Generally, wave equation software is used to estimate the minimum blow count needed to achieve the desired final capacity of a pile. For a design that is only concerned with the bearing capacity, this can work well; however, when the design is governed by uplift assumptions regarding the resistance distribution, additional assumptions must be made and when this changes, the model is no longer valid. An example of this is when two identical piles are installed in close proximity with equal embedment, soil and hammer energy and one has a significantly higher blow count than the other. Both the dynamic formula and a bearing graph would tell the designer that the pile with the higher blow count has the higher capacity, which is probably true. The problem for an uplift design is that this is most likely caused by the toe capacity being higher, either from an obstruction or toe plug, and the uplift resistance of the two piles is most likely similar. In this example, the resistance distribution has changed, making it difficult to correlate the uplift capacity from the blow counts alone. In many situations, blow counts can be misleading, caused by differences in transferred hammer energy, damaged piles and substantial differences between achieved and expected toe capacity.

Dynamic monitoring

Dynamic monitoring works by using an accelerometer and strain gauge located at the top of the pile to monitor forces and velocities traveling through the material. This data is received and monitored by a Pile Driving Analyzer (PDA). As the information is received and monitored real-time, it is also stored for post-installation analysis. Real-time information monitoring can also be provided to engineers located offsite. The post-installation analysis uses the Case Pile Wave Analysis Program (CAPWAP) and is a signal matching procedure which, based on top of pile force and velocity measurements during hammer impact, extracts static and dynamic soil resistances and parameters for pile shaft and pile toe.

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CAPWAP analysis

Following the installation of a driven pile that has been dynamically monitored, a CAPWAP analysis can be conducted based on the data of any single blow during pile installation. This post-processing procedure can be effective in evaluating the soil resistance distribution along the shaft and at the toe, ultimately providing the ability to estimate the total bearing and uplift capacities, as well as solving for unknown dynamic soil parameters. CAPWAP is an effective and efficient method of simulating a Static Load Test and has been shown to compare very favorably to the Static Load Tests. Additionally, CAPWAP is a non-destructive and time efficient tool for determining capacities. Please note that this is a comprehensive software package that requires an in-depth understanding of soil dynamic properties and training from an experienced engineer.

Options	Structures With Failing Blow Counts	Splices Avoided	Cost Savings
Option 1	58	581	$3,573,150
Option 2	58	2212	$13,603,800

Table 1: Cost savings associated with elimination of splices

Option	No. of Structures	No. of Splices Avoided	Cost Savings
Splice elimination	11	472	$2,902,800

Table 2: Cost savings associated with elimination of splices when initial design depth was greater than pile length

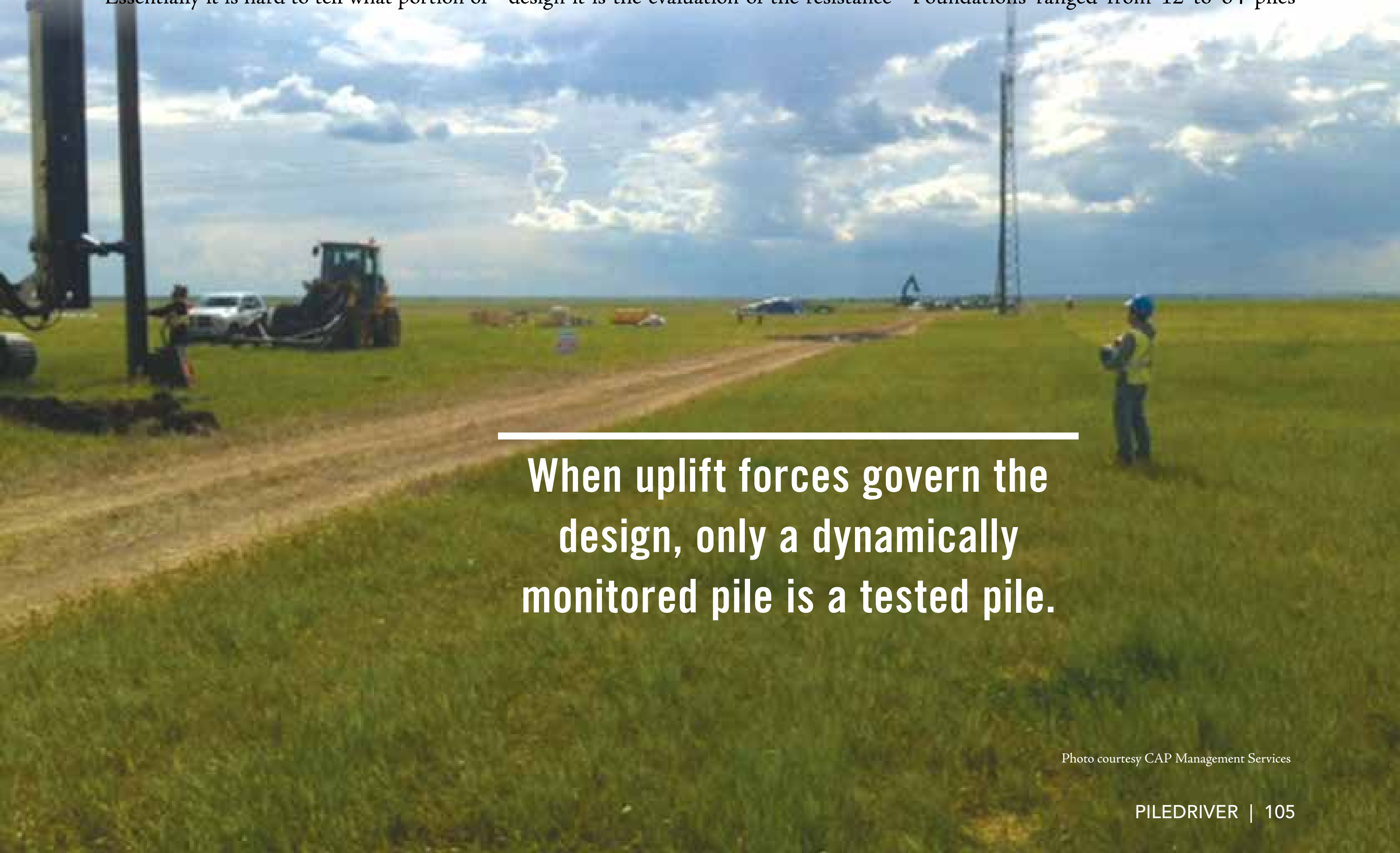
Advantageous to dynamic monitoring

The wave equation software is fundamentally correct, but for an uplift design, the designer must assume a resistance distribution to correlate blow counts to an uplift capacity and if the distribution is incorrectly assumed, the correlation is not valid. Essentially it is hard to tell what portion of the blow count or soil resistance to hammer energy is generated from the toe resistance and what portion comes from the shaft resistance.

Dynamic monitoring and post-processing with CAPWAP software ultimately provides engineers with the most valuable information. This includes, but is not limited to, resistance distribution, dynamic properties, impact energy, pile integrity and stresses in the pile. However, for uplift design it is the evaluation of the resistance distribution that best assists designers, projects and owners alike.

Case study

The following case study will highlight the methods, findings and advantages of dynamic monitoring as applied to a transmission line project in Western Canada. This project consisted of approximately 641 towers and foundations covering a distance of 244km with over 10,000 piles. Foundations ranged from 12 to 64 piles



When uplift forces govern the design, only a dynamically monitored pile is a tested pile.

Photo courtesy CAP Management Services

per foundation, with up to four foundations per tower. At least one pile at each structure was dynamically monitored and analyzed with an additional 158 piles being re-struck to gain local experience for set-up factors of the varying soils for the vast range.

Driving criteria were developed with the aid of geotechnical information, wave equation software and empirical formulas. Three cases are presented below detailing situations in which dynamic monitoring provided added value:

- A case where PDA information avoided additional piles or splices when blow count criteria was not met
- A case where the initial design called for splices, which were avoided by using PDA/CAPWAP analysis
- A case where blow counts passed but PDA data showed additional piles or splices were required as minimum capacities where not met

In all three instances, the PDA program aided the project by avoiding unnecessary piles/splices, switching more expensive and/or labour intensive foundation types to driven piles and promoted a safer design by identifying piles with failing capacity, even when minimum blow counts and bearing capacity were met. This was accomplished by the ability to evaluate the resistance distribution along the pile and at the toe.

Case 1: Piles with failing blow counts

Without the use of PDA data, when a structure has a pile with a failing blow count, the design team would specify either the installation of splices or additional piles. In most situations, splicing was specified for constructability reasons, leaving two splicing options:

- Option 1 – Splice only individual piles with failing blow count
- Option 2 – Splice all piles at each structure with at least one failing blow count

The cost savings associated with avoiding either splicing option is presented below in Table 1. The presented savings are based on a unit cost of $6,150 per splice, including welding, material, labour and equipment cost.

Case 2: Structures that initially called for splices

In total, there were 11 structures that had an initial design, using empirical formulas, that required spliced piles to achieve depths greater than 17m. For these 11 structures, a hold point was established after all piles were installed to 17m. PDA data was then analyzed within 24 hours to determine if the splices were needed. Remarkably, all 11 structures passed minimum capacity, removing the requirement for splicing. In all 11 cases, splices would not have been avoided without PDA. The cost saving of these design changes are presented below in Table 2.

Case 3: Structures that passed blow count criteria but failed to meet minimum capacity

In addition to the savings that PDA and CAPWAP software provide to refining a design, they also help to promote a safe design by accurately estimating pile-soil resistance. For this project, 36 structures had passing blow counts but upon CAPWAP analysis showed that the uplift resistances had not been met at design depth. Of these 36 structures, four of them required splicing of all

the piles, as the capacities were much lower than design criteria and 32 of them were close to design capacity criteria and only required one to four piles added per structure.

Case study conclusions

The case study results document a clear picture: a large number of initial assumptions, capacity calculations and blow counts – derived from wave equation software, empirical formulas and geotechnical assessments – can prove misleading when comparing them to the uplift estimations of PDA and CAPWAP data. While some structures called for splices where the dynamic results suggested splices were not needed, others required splices to meet minimum uplift capacity even when the blow counts were high; countless more structures had failing blow counts that proved to meet design criteria. In addition, through the use of dynamic monitoring, all of the grillage and caisson foundations were changed to driven piles as a result of the integrity that could be accurately monitored. The ability to evaluate the resistance distribution with the use of PDA and CAPWAP software proved to be an instrumental part of this project's success. Here, the PDA program's success was compounded by the fact that only an exponential amount of time and money on static load test could have refined the design in a similar manner and that in general, blow counts, even when derived from wave equation software, are misleading when the design is governed by the uplift resistance.

Summary

In general, when an uplift design is not dynamically monitored (PDA), the design is generally governed by embedment depths and proven/expected unit resistances with the use of static load test. In this case, there are many unknown factors and assumptions that need to be made to competently correlate an uplift capacity to a blow count without using a larger factor of safety. This leads to a more expensive and lengthy project that still might have some piles with uplift resistances that do not meet design criteria. The case study presented in this article demonstrates, for uplift design, that dynamic monitoring provides more favorable and site specific or event information than blow count criteria, even when they are derived from wave equation software. When reviewing the results of the transmission line project, it is clear that without an integrated dynamic monitoring program some structures could have not met the minimum design capacity requirements which could have led to failures, and countless structures would have been unnecessarily spliced or additional piles installed. This would have made the project more costly and labour extensive; therefore, the dynamic monitoring program promoted a more sustainable design while maintaining design safety thresholds. In closing, the overall goal of this study and the case results presented in this paper is to provide context and, hopefully, initiate further discussion on field testing methods and standards for all driven pile foundations governed by uplift and the benefits of dynamic pile monitoring. ▼