What We Know About High-Strain Dynamic Testing of Steel Pipe Piles with Concrete Plugs

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ABSTRACT Open toe steel pipe piles in granular soils often fail to plug during impact driving. This can result in excessively long piles to achieve the designer's termination criteria and corresponding required geotechnical resistance. Plugging of piles can be induced using either an internal diaphragm plate or a concrete plug of limited length. This paper will review the results of simulations and actual high-strain dynamic testing (HSDT) completed on piles with a concrete plug along with a discussion on the challenges related to signal matching. The paper provides general, yet preliminary, guidance on dynamic testing and signal matching of steel pipe piles with concrete plugs.

Introduction

Driven steel pipe piles, widely used as bridge foundation support in the transportation and energy sectors, often require a minimum embedment for lateral resistance due to high seismic demands and for scour protection. Where the foundation soils are particularly dense or cobbles and boulders are present above the desired pile toe elevation, there is a risk of encountering early refusal or sustaining pile damage during impact driving. To control these risks, piles may be initially advanced by drilling to some minimum embedment, followed by impact driving to the specified termination criterion. This installation sequence may require a significant amount of additional pipe if the piles core. To increase the pile toe resistance, steel pipe piles are sometimes modified during installation by placement of concrete over a limited length of the interior of the pile to create a plug. This paper will review some of the challenges related to this approach, in particular the interpretation of high-strain dynamic testing (HSDT) results and provide a suggested approach to testing and signal matching.

Effect of plug on pile impedance and behaviour

Typically, HSDT is conducted on hollow steel pipe piles (i.e., no concrete plug) with a closed or open toe, or on fully-concreted pipe piles. In both cases, the pile impedance is known, or can be defined relatively easily, and is often constant. Construction of a concrete plug introduces a significant impedance contrast along the pile which is reflected in the HSDT force (F) and impedance times velocity (Zv) signals, and upwave [U↑ = (F – Zv)/2]. The impedance contrast along the concreted section can be substantially larger than that of the steel pipe section depending on the pile diameter. As noted in CFEM 2006 and Fellenius (2023), impedance contrasts of 2 or more have the potential to result in driving difficulties.

The construction of a concrete plug also introduces uncertainties related to the pile properties (i.e., composite modulus, density, etc.) and behaviour (i.e., bond versus slippage condition at the concrete/steel interface) of the concreted section of the pile. Separating the effects of the impedance change introduced by the concrete plug and the behaviour of the concrete plug, from the resistance of the soil surrounding the pile with any degree of confidence is difficult. This can also be further complicated by the relative location of the concrete plug along the pile and the relative length of the concrete plug.

Simulation of the dynamic response of open toe pipe pile with and without concrete plug

To demonstrate the effect of a significant impedance contrast on the dynamic response of a pile, simulations were conducted using the software AllWave-PDP by Allnamics of The Netherlands which uses the Method of Characteristics. A 610 mm x 12.7 mm open toe pipe pile with an embedment of 30 m was selected. The shaft resistance was assumed to increase linearly with depth from zero at ground surface to a maximum of 60 kPa at the toe. For the base case condition (i.e., pipe pile with no concrete plug), a toe resistance of 30 MPa (i.e.,

q_c = 30 MPa) was applied only to the steel section of the pile toe, which represents coring behaviour. Shaft and toe damping were assumed to be proportional to the modelled shaft and toe resistances and soil quakes were 2.5 mm. Fig. 1 shows the resulting F and Zv traces versus time and Fig. 2 shows the corresponding plot of U↑ versus time. Note that the pile is shown schematically in the bottom left of the figures and the toe of the pile is indicated by the vertical dashed line.

Fig. 1. F and Zv versus time for unplugged pile simulation (base case).

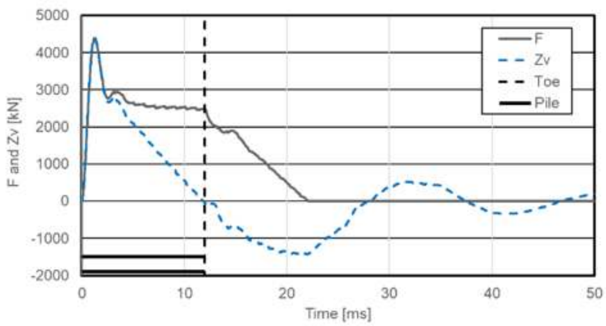
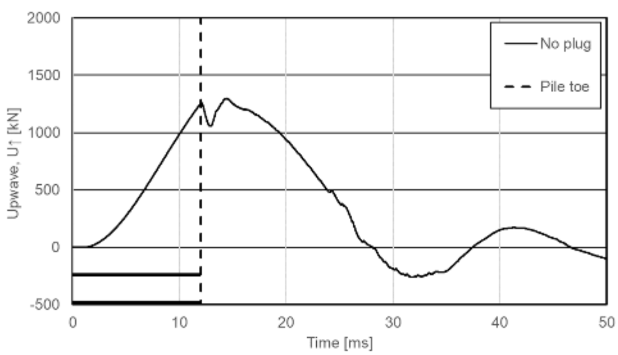
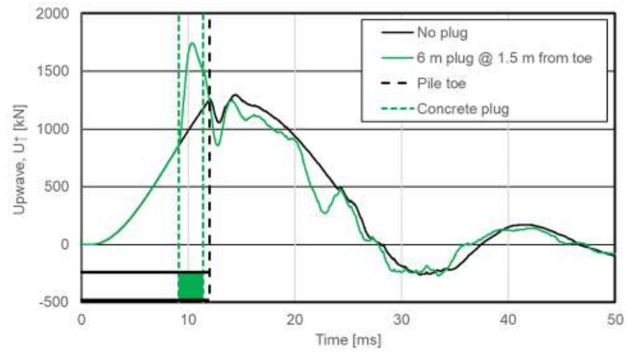


Fig. 2. Upwave U↑ versus time for unplugged pile simulation (base case).



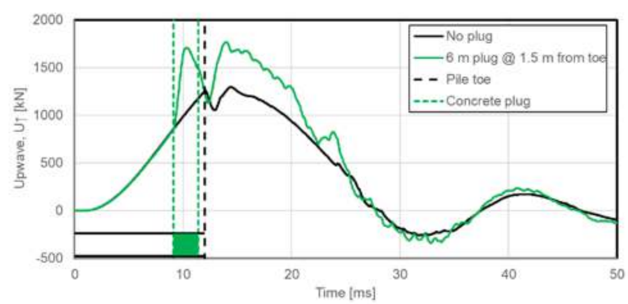
To visualize the effect of a concrete plug, we considered two lengths of plugs (i.e., 6 m and 12 m), both constructed 1.5 m from the pile toe. For both cases, the dynamic response of the pile was modelled in two stages. In the first stage shown in Fig. 3 (Scenario #1), the shaft and end bearing resistances were modelled in the same manner as the base case. The pile wall thickness was doubled within the 6 m concrete plug section to reflect the impedance change. The pile and concrete plug are shown schematically in the lower left of the figure. The green dashed vertical line represents the limits (top and bottom) of the concrete plug and the black dashed line the location of the pile toe. This stage represents the pile response during the first few blows of a dynamic loading test conducted after the concrete has set and is essentially considered to be a coring condition.

Fig. 3. Simulation of the base case scenario (open toe pile with no concrete plug) and Scenario #1 (increased pile wall thickness along 6 m concrete plug section)



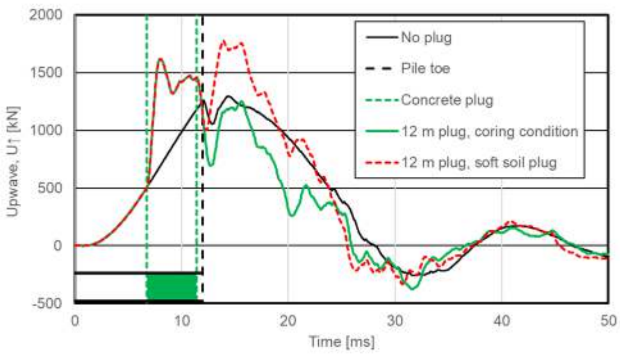
In the second stage shown in Fig. 4 (Scenario #2), the shaft resistance was modelled in the same manner as the base case and the pile wall thickness was doubled within the concrete plug section similar to the first stage. The end bearing was modelled as a closed toe condition and was assigned a value of 6 MPa which represents the equivalent of a soft soil plug condition (i.e., $q_{b10} = 0.2q_c$ = 6 MPa) (Fleming et al., 2009).

Fig. 4. Simulation of the base case scenario (open toe pile with no concrete plug) and Scenario #2 (increased pile wall thickness along 6 m concrete plug section and an end bearing resistance corresponding to a soft plugged pile)



In the second case, everything was modelled the same except the length of the plug which was doubled. Fig. 5 shows the upwaves for the base case (no plug), Scenario #3 which is an early blow (coring condition similar to Scenario #1) and Scenario #4 which is a later blow when a soft soil plug starts to develop.

Fig. 5. Simulation of the base case scenario (open toe pile with no concrete plug), Scenario #3 (increased pile wall thickness along 12 m concrete plug section and coring condition) and Scenario #4 (soft soil plug condition)



By inspection, the concrete plug overwhelms the dynamic response of the pile. Further, the measured response becomes more complex during the transition from the coring condition (initial blows) to later blows. The reality in the field is that it is rare to find a uniform soil deposit as was used in this example and even more rare to find a concrete plug that performs as assumed in the model herein (i.e., equivalent to an increase in pile wall thickness).

Recent case histories

In 2022 and 2023 the authors were involved with HSDT and signal matching on several projects that included the use of concrete plugs. On one project, piles were subjected to HSDT before and after placement of the concrete plugs.

At this site, the subsurface stratigraphy consisted of compact to dense granular fill over coarse-grained alluvial deposits underlain by sand with some silt and a trace to some gravel. The foundations comprised 914 mm x 19.1 mm steel pipe piles that were drilled in through the coarse-grained deposits and then advanced by impact driving using a Junttan HHK12 hydraulic hammer with a 12,000 kg ram. The piles were advanced to 45 m to 50 m embedment without attaining the desired termination criterion. In hopes of inducing plugging and in turn increasing the penetration resistance, concrete plugs were added to some of the piles.

Using the available drilling equipment which had a limited reach compared to the pile embedments, the concrete plugs were only installed to about 26 m below the pile head. This resulted in concrete plugs that were constructed relatively high in the piles. Nonetheless, upon redrive, the penetration resistance increased from about 20 blows per 250 mm before placement of the concrete plug to refusal using the same hammer that was operated at the maximum energy setting of about 160 kJ. In comparison, piles without concrete plugs only saw the penetration resistance increase to 30 blows per 250 mm on redrive.

Prior to signal matching, the successive measured upwave signals were plotted from the testing completed before and after placement of the concrete plug. This process of comparing multiple signals is referred to as signal stacking and is the preferred “old school” approach to analysing low strain integrity test results in Europe (Bielefeld et al., 2022). With signal stacking, multiple measured signals are plotted to evaluate and compare the quality of the measured signals. In the case of sonic integrity testing (SIT) and HSDT, signal stacking can be used to evaluate the performance of individual piles or groups of piles and to identify outliers as similar sized piles of similar length installed in the same soil strata should show the same reflections. This method can then be used to identify signals or piles that differ from the group. Where this method is most powerful is when it comes to assessing the integrity of an anomalous pile. The two-phase process starts with signal matching conducted on the average signal assuming a sound or uniform pile to estimate the soil resistance distribution. With the calculated soil resistance distribution, signal matching is then conducted on the signal for the anomalous pile and the pile model is changed until a good match is obtained. The outcome of this two-phase process is an estimate of the pile impedance with depth. According to Bielefeld et al., the advantage of this approach is that “smaller anomalies can be detected than in the traditional qualitative interpretation method”. While this overall approach has gained widespread acceptance in Europe for users of the low strain integrity testing method, these concepts have not really caught on with practitioners in the HSDT domain.

Fig. 6 represents the stacking of the upwave signals of blow numbers BN 4 to BN 14 from the testing completed on the non-concreted pile. By inspection, the upwave signals are relatively consistent from blow to blow, particularly before the pile toe at 2L/c or about 39 ms.

Fig. 7 represents the stacking of the upwave signals of select blow numbers between BN 51 and BN 96, from the testing completed after the placement of the concrete plug. The plug measured 17.7 m in length and was constructed about 24 m above the pile toe. Similar to Fig. 6, the upwave signals are relatively consistent from blow to blow.

Fig. 6. Select stacked upwaves for DLT conducted on Pile PN12 without concrete plug

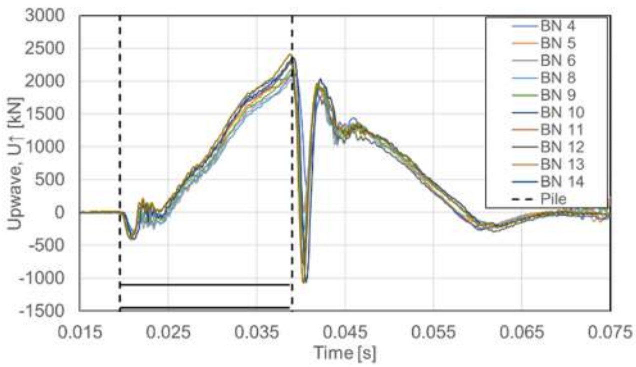


Fig. 7. Select stacked upwaves for DLT conducted on Pile PN12 with concrete plug

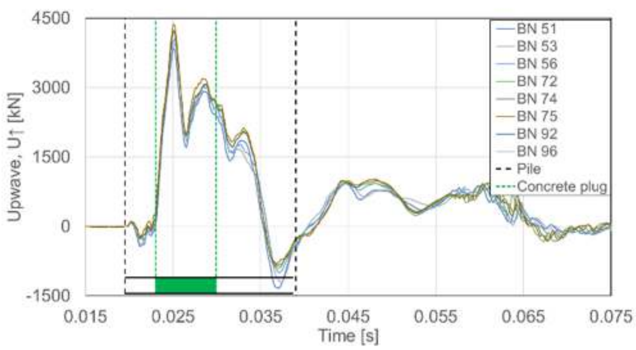
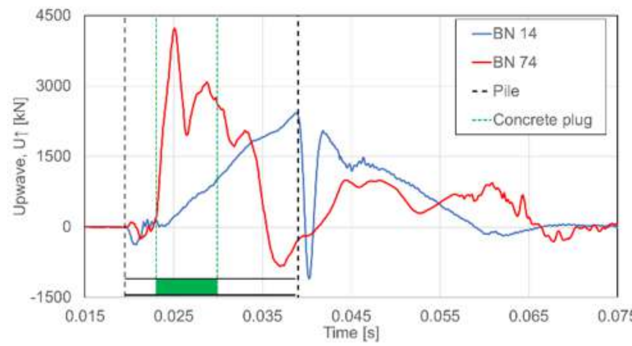


Fig. 8 provides a direct comparison of the upwave signals from the testing completed before (BN 14) and after the placement of the concrete plug (BN 74). The comparison clearly demonstrates the effect of the concrete plug on the dynamic response of the pile. Further, the dynamic response of the pile below the concrete plug location is also markedly affected between 0.03 and 0.04 seconds (see figure). This represents the section of the pile between the concrete plug and the pile toe.

Signal matching was initially attempted by analysing the HSDT results of the pile with the concrete plug. The analysis was time consuming, the matches relatively poor and the results were questionable given the uncertainty in separating the effects of the impedance contrast from the soil resistance. The analysis was further complicated by the excessive length and relatively shallow location of the concrete plug.

To reduce the uncertainties in signal matching, the authors proceeded with an alternative analysis where the shaft resistance parameters (i.e., yield and damping) were assessed from the HSDT completed before placement of the concrete plug as is done with SIT in Europe. Fig. 9 shows the signal matching results of blow BN14 that was completed using the software IMPACT (Randolph, 2008). The figure includes plots of force and impedance times velocity, upwave, displacement and work versus time and the accompanying match. Also shown is the shaft resistance distribution, a plot of pile head displacement versus work and a summary of the estimated resistances, etc.

Fig. 8. Comparison of select upwaves for DLTs conducted on Pile PN12 with and without concrete plug



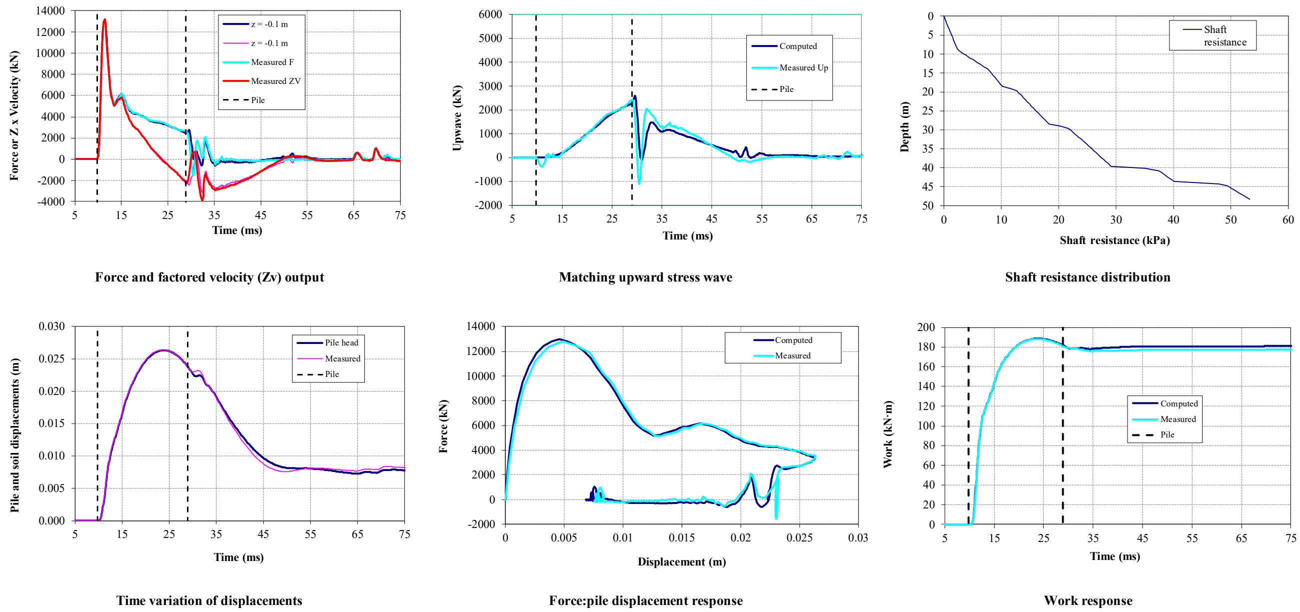
The match quality was reasonably good, with a mobilized shaft resistance of 2.6 MN and a toe resistance of 2.6 MN.

Signal matching was subsequently completed on the HSDT results collected after the installation of the concrete plug. Blow BN74 was selected to complete the analysis using IMPACT. Using the shaft resistance derived from the former analysis, the only parameters that were varied were the pile impedance along the concrete plug section and the pile toe resistance. The concrete plug was modelled as a series of seven lumped masses of 2.5 m in length. The lumped masses were initially set equal to the actual mass of concrete over the 2.5 m length but were reduced in the top three masses until a reasonable match was obtained. The end bearing was modelled as a closed toe condition.

The analysis was completed with relatively little effort to obtain a good match quality. Fig. 10 shows the signal matching results of Blow BN74. The analysis indicated a mobilized shaft resistance of 2.6 MN and toe resistance of 3.9 MN, representing an increase in resistance of about 1.3 MN.

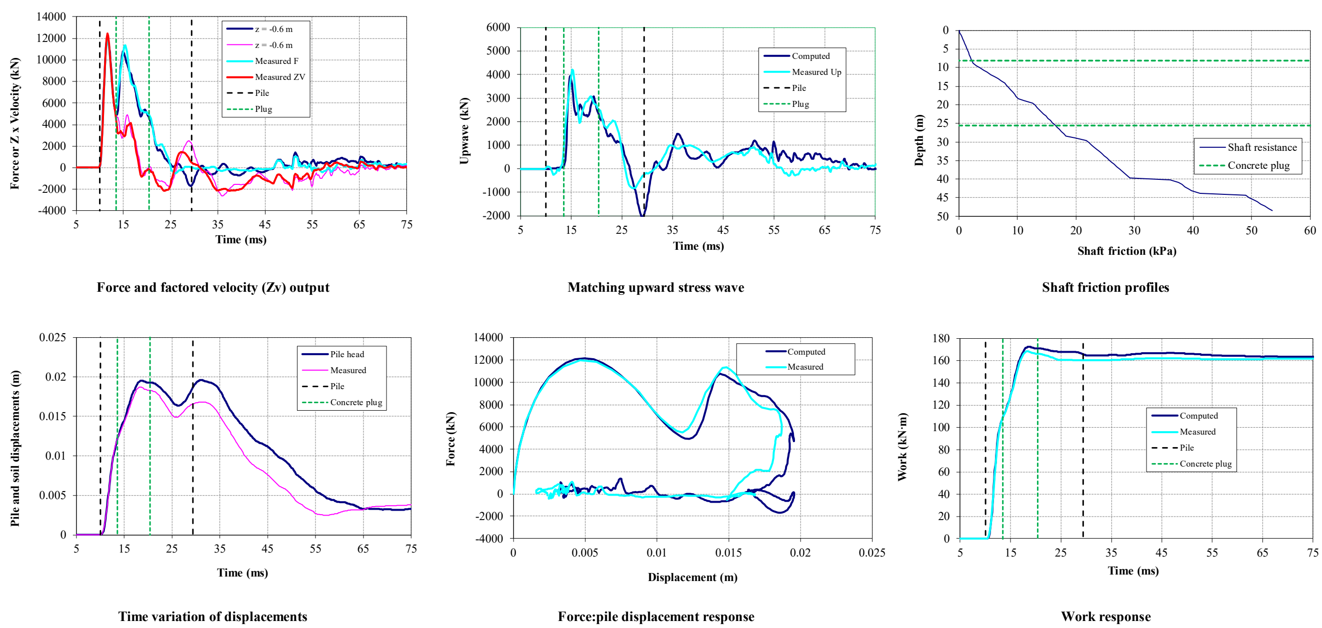
Using the same two stage approach, an independent analysis was completed using the software AllWave DLT by Allnamics. Relatively little effort was required to complete the analysis, with very similar results obtained. In AllWave-DLT, the concrete plug section of the pile was modelled as a solid concrete section.

Fig. 9. Signal matching results for blow BN14, without concrete plug



Signal Matching Output									
Case No.	Pile Embed. m	Shaft Capacity kN	Base Capacity kN	Total Capacity kN	Maximum Energy kJ	Maximum Disp. mm	Permanent Set/Blow mm	Maximum Pile Stress MPa	Minimum Pile Stress MPa
1	48.6	2601	2624	5225	189	26.1	7.4	243	-13

Fig. 10. Signal matching results for blow BN74, with concrete plug



Signal Matching Output									
Case No.	Pile Embed. m	Shaft Capacity kN	Base Capacity kN	Total Capacity kN	Maximum Energy kJ	Maximum Disp. mm	Permanent Set/Blow mm	Maximum Pile Stress MPa	Minimum Pile Stress MPa
1	48.8	2632	3937	6569	173	19.6	3.3	323	-62

Summary

Open toe, driven steel pipe piles may be modified with a concrete plug to increase toe resistance. However, signal matching of such piles must consider increased uncertainty that is introduced by the impedance contrast along the pile section. Based on the authors' recent experience, the reliability of signal matching of piles with concrete plugs can be improved by testing the same pile prior to concreting or an adjacent open toe pile of similar dimensions and installed using the same procedure. In this manner, the shaft resistance distribution can be established by signal matching of the open toe pile. Then, the analysis of the plugged pile can focus on matching the effects of the pile impedance change and the increase in toe resistance.

The authors' proposed two stage approach to signal matching was completed using IMPACT and AllWave-DLT software programs, with relatively consistent results obtained. However, additional testing is required to confirm the applicability and limitations of this approach. Further, a detailed testing program on future projects that include static loading test(s) or possibly rapid load testing would provide an opportunity to validate the assumptions. Such a testing program could also be used to assess whether the use of a concrete plug is required.

The following are the authors' preliminary guidance for sizing of concrete plugs and dynamic testing and signal matching of such piles.

- Ideally, the concrete plug should be constructed as close as practicable to the toe to avoid additional reflections before 2L/c in HSDT. The concrete plug should be constructed within a few diameters of the toe. Sometimes, however, this criterion may not be achievable for constructability reasons.
- The length of the concrete plug should be as short as possible.
- The concrete plug dimensions and construction details must be properly documented to eliminate additional uncertainty, particularly regarding plug length and debonding.
- Signal stacking provides insight on the behaviour of the concrete plug with successive blows and the overall signal quality.
- Pile drivability simulations must include the concrete plug to determine termination criterion.

References

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