PDA measurements: fact or fiction.

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ABSTRACT

Pile Driving Analyzer (PDA) measurements have been used since the 1970's to monitor the pile driving process, driving stresses in the pile, pile integrity, as well as the soil resistance magnitude and resistance distribution and to judge the hammer performance in relation to pile driveability predictions carried out by 1-D simulation programs. Pile strains and axial pile accelerations are in general measured at 1 or 2 location along the pile 180° divided over the circumference, with each location composed of 2 or 4 pairs of sensors, or at 4 locations, 90° divided over the circumference. In general, for each hammer blow, these strain and acceleration measurements are recorded by special devices mounted to the outside of the pile wall. The results of the measured strains and accelerations are averaged and the final result gives indications about the behaviour of the whole pile. Although the assumption of a 1D system may in the past have been more or less accurate for small hammers and small diameter piles, for the present hammers with higher rated energies, and for current monopiles for wind energy farms with top pile diameters ranging from 6 m to 8 m this is certainly not the case anymore. In these conditions, an attempt to determine the behaviour of these piles during pile driving by measuring just at 2 or 4 local points over the circumference can lead to errors in the interpretation of the results. PDA measurements can be affected by the bending of the pile wall introduced by the deformation of the pile driving equipment, the unevenness of the pile top resulting in insufficient contact between pile top and anvil, not perfectly aligned impact of the ram onto the pile due to eccentricity offsets or inclinations, etc., as well as by assumptions made during the post-processing of the PDA measurement results.
In this paper, an analysis of PDA measurements executed for a recently installed offshore windfarm is performed and a comparison with finite element results is made to determine the effect of the parameters mentioned above on the measurement accuracy. It will be shown that these effects can be quite considerable and can lead to for example a large spreading in the ENTHRU energy following from the PDA measurements.

Keywords: PDA, impact pile driving, monopiles, measurement, finite element

1 INTRODUCTION

The measurement of pile installation operations by means of the Pile Dynamic Analyzer (PDA) method has been adopted since the early 70's (Beim et al., 1998) to determine pile bearing capacities and to monitor the structural behaviour of the foundation and hammer performance during installation (Alwalan and El Naggar, 2020).

PDA method consists of a data acquisition unit (DAQ) coupled with accelerometers and strain gauges installed on the pile, to determine velocity and force data at certain pile locations. In general, acceleration and strain measurements could be executed in accordance with industry standards (e.g. ISO 22477-10:2016 or ASTM Standard D4945) that prescribe the sensor arrangement, configuration and best practices for DAQ settings

Usually, real time data-analysis during installation is not performed although correlation with expected driveability results can be executed shortly after piling (Lee et al., 2016; Zhussupbekova et al., 2017) by application of 1D stress wave theory (Smith, 1960; Middendorp and Verbeek, 2006), theoretical basis of the mono-dimensional (1D) calculation models used in commercial software like TNOWAVE (TNO report, 1996), or GRLWEAP (Pile Dynamics, 2005). The assumption of a 1D hammer-pile system underlying PDA and stress wave theory has obvious limitations when applied to the large monopile foundations currently developed for the offshore wind market, with top diameters in ranging from 6 m to 8 m. These large piles and the large anvils used for installation are more flexible in comparison to the smaller piles and anvils used in the previous years, and methods based on 1D bodies do not provide accurate results in terms of forces at the pile top for example (Orlando et al., 2021; Ligthart and Orlando, 2022).

In this paper, PDA measurements from installation of offshore wind large steel monopiles and the main findings of such measurements will be presented. The experimental data will be compared with finite element (FE) calculations. Finally, limitations and possible errors in the analysis of PDA measurements will be presented and discussed.

2 PDA MEASUREMENT CAMPAIGN

This measurement campaign was executed during the offshore installation of 4 conical large diameter steel monopiles of which one will be discussed in detail in this paper (pile data are confidential, therefore no specific details about the design can be provided).

2.1 IQIP Pile Driving Equipment

The piles were driven using the IQIP equipment listed in Table 1. Measuring of the hammer impact energy is executed by the hammer control system and recorded for subsequent analysis.

Driving settings of the hammer during installation are confidential and cannot be provided in this paper.

Table 1. Pile driving configuration.

Hammer	IQIP Hydrohammer S-4000
Anvil	5.5 m
Ring Anvil	6.5 m
Pile	4 different geometries

2.2 PDA Measurement Equipment

The PDA measurement system provided by Pile Dynamics, Inc. has been used to acquire the signals of 4 strain gauges and 2 accelerometers for each pile. Installation of the sensors has been executed at a minimum distance of 1.5 times the outer top pile diameter, by placing the strain gauges symmetrically at 90° relative to each other and the 2 accelerometers diametrically opposite at 180° from each other. Measurement settings were in line with the guidelines of the ASTM Standard D4945.

2.3 Experimental results

In Fig. 1 plots of the acceleration and strain measurements are reported for a pile during one of the analysed blows.

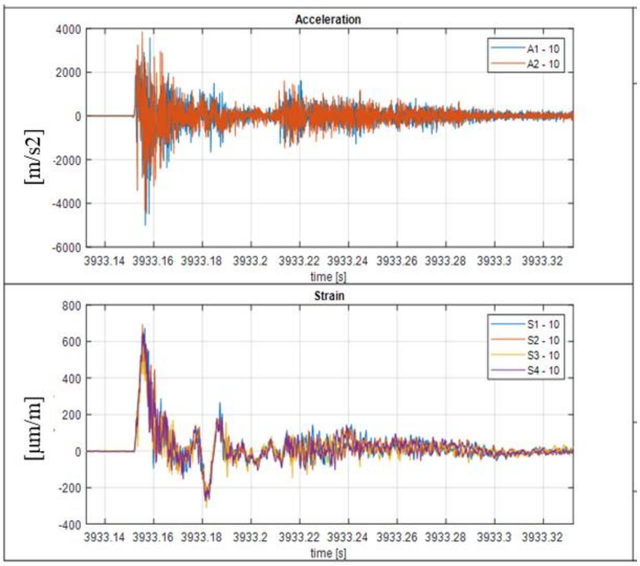

Fig. 1. PDA accelerations and strain measurements.

The main focus of this experimental campaign was the validation of the hammer performances during pile driving, therefore the results discussed in this chapter are the ENTHRU energy, defined as the energy that is transferred to the pile, and the longitudinal impact force in the pile force (F). The two quantities are related by a theoretical formulation, namely the integral of the downward travelling impact force (F_{down}) times the pile longitudinal velocity (v_{pile}) over the impact time duration, which can both be measured by PDA:

$$E_{ENTRHU} = \int_{Tstart\ impact}^{Tend\ impact} F_{down} \cdot v_{pile} \cdot dt \qquad (1)$$

In Fig. 2 plots of the recorded hammer and ENTHRU energies are shown for one of the analysed piles as a function of the pile penetration.

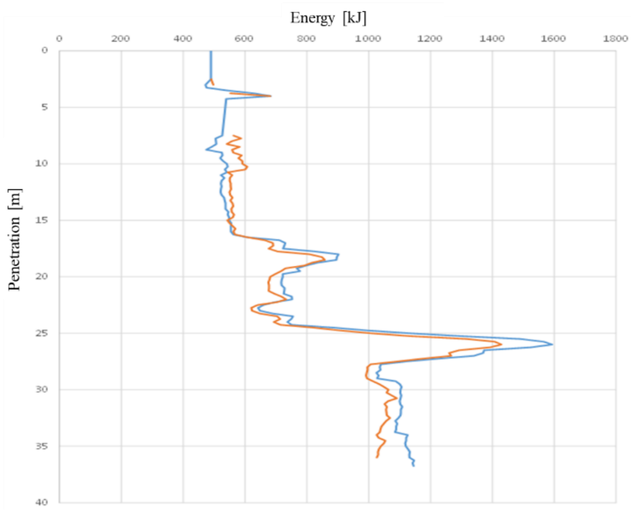

Fig. 2. Recorded impact hammer (in blue) and ENTHRU (in orange) energies per pile penetration.

Fig. 2 shows that in the first 15 m of penetration the recorded hammer impact energy is slightly below the measured PDA ENTHRU energy, which at first sight represents a paradox but can be due to measurement errors in both the hammer or in the PDA measurement system. Since the focus of this document is on the PDA measurement technique, the hammer measuring system accuracy is not investigated further in this paper; however it should be mentioned that investigations on the hammer measurement system have demonstrated an accuracy of c.a. +/- 10% of the impact energy at low energies. This accuracy improves significantly at higher impact energies. On the other hand, the accuracy of the PDA measurement can be affected by several parameters, discussed in the next chapter.

2.4 Errors in the PDA measurements

Generally, the accuracy of PDA measurements is affected by both the signal acquisition and post-processing errors.

Signal acquisition errors can be due to:

1. *The accuracy of the applied sensors*, where accelerometers must have a sufficiently high resonance frequency, low temperature dependency and a very small zero offset with good linearity. Strain gauges accuracy errors due to temperature effects must also be compensated for.
2. *Sensor mounting on the pile wall*, that must be stiff enough to avoid introducing spurious frequencies in the acquired signals.
3. *Effects of lead wires* between the sensors and the acquisition unit, that can easily reach lengths of 100 m, resulting in potential effects on the measured signals due to the electrical properties of such cables that must be compensated, unless not included in the sensors themselves.
4. *The measurement duration*, that should start before each blow, and ends after the blow once the pile is again at rest. In case the measurement is stopped when a pile oscillation is still present, effects on the accuracy of the ENTHRU energy are found.
5. *The strain measurement location on the pile* outer diameter, that obviously results in inaccuracies for the determination of the average pile force due to local bending effects, especially for large monopiles. Errors in the range of +/- 4% can be expected on the pile impact force due to this phenomenon in case of conical piles. Measuring in close proximity of the pile top, or close to the transition from cylindrical to conical, can lead to even higher errors due to increased bending effects at that location.
6. *The evenness of the distribution of the pile top force over the pile circumference*, that can be affected by, for example, the stiffness of anvil and ring anvil, eccentricity and inclination of the hammer relative to the anvil, unevenness of the pile top. The combination of these “defects” will lead to errors in the evaluation of PDA measurements, especially if only 2 accelerometers and 2 strain gauges are applied for each measured pile section. An impact force increase of c.a. 25% can be found due to this phenomenon.

The main post-processing errors, to be considered as errors in the evaluation of the recorded measurements, can be listed in the following as:

1. *Selection of reliable signals*, as shown for example in Fig. 3, where it is clear that in this particular measurement strain gauge no. 3 measures significantly lower strain than the other sensors. The calculated ENTHRU energy will be an underestimation when based on all 4 strain gauges. This error due to results interpretation can arise, for example, if uneven contact at the pile top occurred for that particular blow.
2. *Integration of the acceleration signals* to determine the velocity of the pile wall, that must be executed to correct for possible non-zero values of the acceleration at the end of the measurement file as discussed above. For example, subtracting a “mean acceleration value” from the measured data can be done to correct this zero offset as well as non-linearity in the accelerometers after which the acceleration data can be integrated over time for accurate velocity calculations. In Fig. 4 the uncorrected and corrected pile velocity signals calculated from the PDA measurement of one blow show the potential errors introduced in the velocity signals using “raw” data.

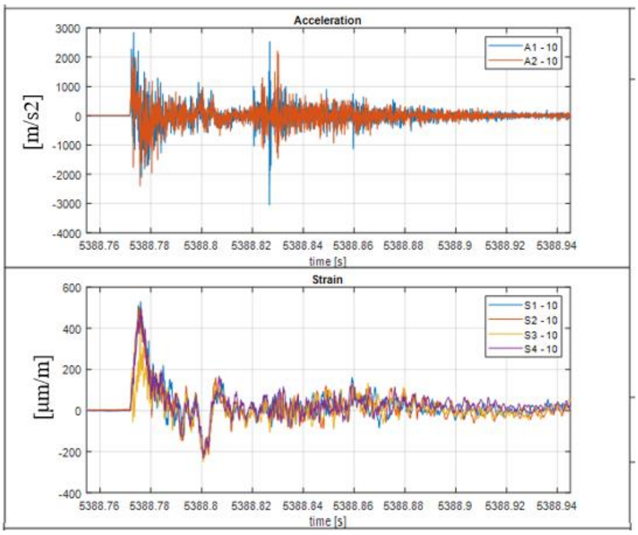

Fig. 3. Post-processing error due to signal selection.

3 FE ANALYSES AND PDA COMPARISONS

To have a deeper understanding of the different physical phenomena affecting pile driving, several FE dynamic calculations have been executed in ANSYS on

2D axisymmetric models representative of the actual driving conditions. In Fig. 5 a generic model used in the calculation is shown, both with and without sleeve.

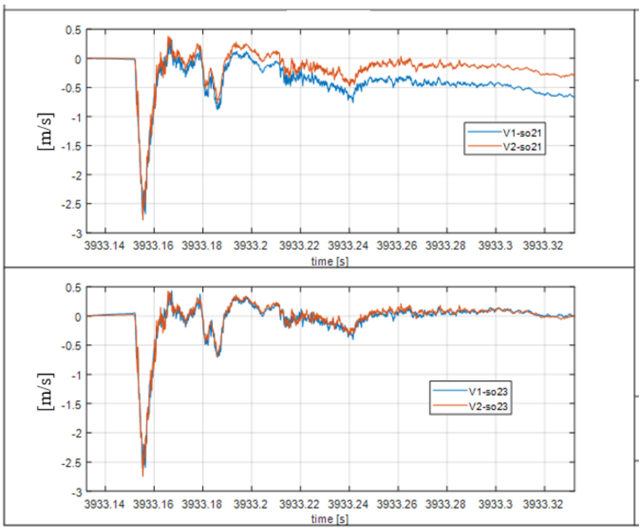

Fig. 4. Uncorrected (top) and corrected (bottom) calculated pile velocity signals.

Single blows with different modelling assumptions have been analysed to correlate numerical and experimental results and to understand the main parameters affecting pile driving and PDA measurements. A full description of the results of these FE calculations is not part of the scope of this paper, whereas the main parameters affecting the ENTHRU energy will be discussed.

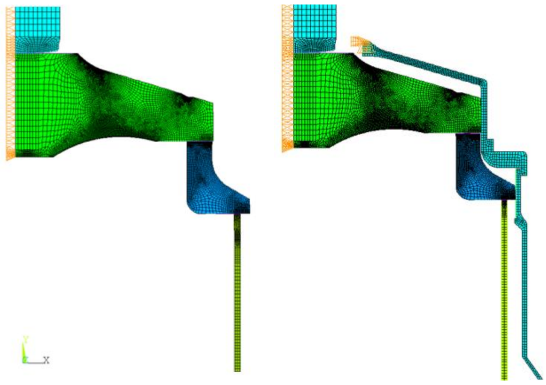

Fig. 5. ANSYS FE models, without (left) and with (right) sleeve.

In general, in Fig. 6 it can be seen that "standard" impact calculations, namely without soil/water/sleeve interaction, produce good correlation with PDA measurements within the first 25 ms in terms of pile impact force and velocity, but result in an overestimation of the ENTHRU energy due to differences in the descending part of the impact force and velocity.

After several investigation, it was determined that the interaction of the anvil, the ring anvil and the pile wall with the sleeve has the biggest influence in reducing the errors on the calculated ENTHRU energy.

In Fig. 7 the results extracted from a FE calculation including interaction between the ring anvil and the sleeve shows an improved correlation between numerical and experimental results.

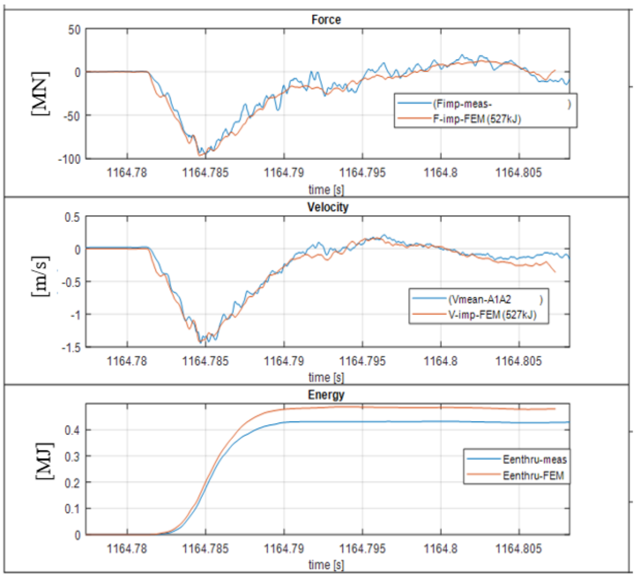

Fig. 6. Numerical (orange) vs. measured (blue) signals for a standard impact calculation.

The improved correlation in terms of impact force and final ENTHRU energy of Fig. 7 can be explained with the improved correlation during the descending part of the impact force.

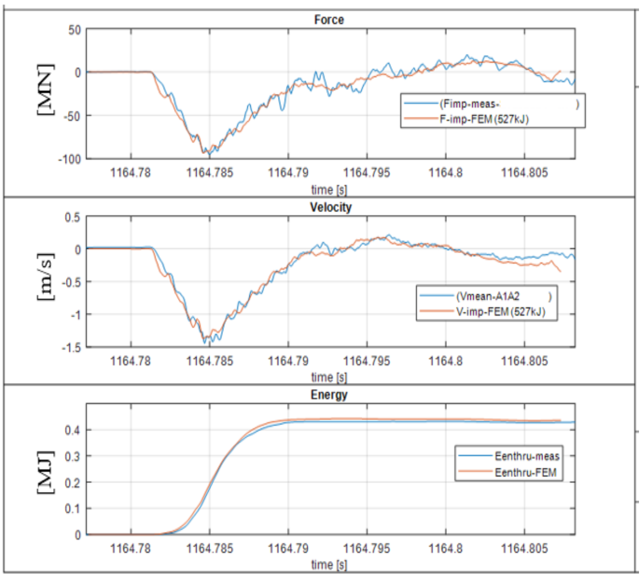

Fig. 7. Numerical (orange) vs. measured (blue) signals for an impact calculation including ring anvil/sleeve interaction.

From FE analyses, the following effects of the analysed driving equipment on the ENTHRU energy calculations were found:

1. *The gravity acting on the ram, anvil and ring anvil.* During the contact period between ram, anvil, ring anvil and pile gravity adds energy to these components. This energy is added to the kinetic of the ram and is transferred to the pile. This energy addition is linearly dependent on the impact energy, or impact velocity, as shown in Fig. 8 by the green line.
2. *The cap pressure and the hydraulic pressure acting on the ram.* The cap pressure accelerates the ram downwards, while the pressure resistance in the hydraulic system decelerates the ram. During the contact period between ram and anvil these pressures add energy to the kinetic energy of the ram that is transferred to the anvil. At maximum impact energy, c.a. 1% of the energy is added due to this effect.
3. *The friction between the sleeve and the anvil, ring anvil and pile wall.* This friction leads to a reduction of the transferred energy from the ram to the pile when contact between the sleeve and the other components is present. This energy loss is for a given configuration linearly dependent on the impact energy as shown by the blue curve of Fig. 8. This friction is only present when there is contact between the sleeve and the other components. Due to the dynamics of the impact, this contact situation can vary from blow to blow. Thus, blows with energy loss due to these friction effects are possible as well as blows without this energy loss. This can lead to a noticeable difference in the energy transfer efficiency between 2 successive blows.
4. *The difference in piles impedance*, that results limited for the investigated piles and therefore this energy loss can be considered to be linearly dependent on the impact energy as shown by the red curve of Fig. 8.

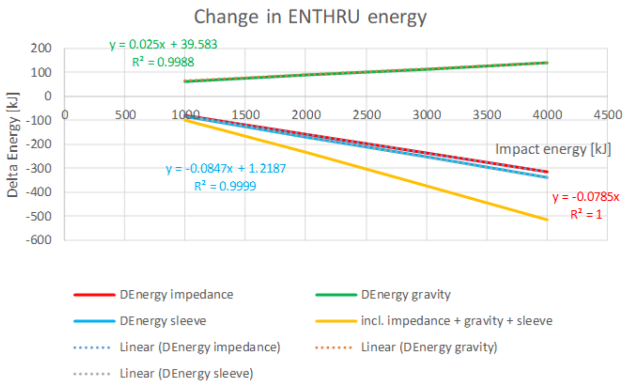

Fig. 8. Change in ENTHRU energy as a function of impact energy investigated by FE.

In FE, the combined effect of the above phenomena at maximum impact energy, e.g. 4000 kJ, can result in a variation in impact energy from -546 kJ to -93 kJ, whereas the deviation at minimum impact energy, e.g. 400 kJ, can vary from -76 kJ to +69 kJ. These deviations of the ENTHRU energy can be represented on the graph of Fig. 9, where the line ‘FEA No Gravity’ presents the lower limit of the estimated deviation of the ENTHRU energy for “standard” FE calculations without gravity effects; the line ‘FEA + Sleeve Friction’ presents the lower limit of the estimated deviation of the ENTHRU energy when sleeve friction is present. The location of the line ‘FEA No Gravity’ is mostly determined by the impedance effects of the anvil, ring anvil and pile. The ‘FEA + Gravity’ line represents the upper limit of the ENTHRU energy deviation when the gravity effects are included in FEA, without accounting for sleeve friction effects.

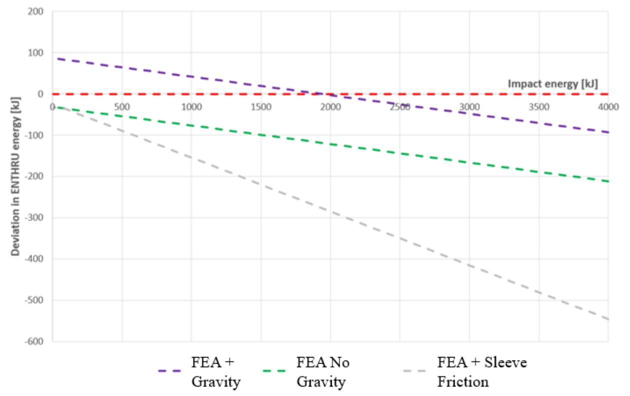

Fig. 9. Upper and lower limits of the ENTHRU energy deviation based on FE calculations.

4 PDA CRITICAL REVIEW

In this chapter a critical review of the executed PDA measurement is reported for one of the measured piles. In particular, in Fig. 10, a plot showing the difference between ENTHRU energy and the hammer impact energy is reported, showing the following data:

- *Raw data*, all the raw data measured by the PDA system.
- *FEA + Gravity, FEA No Gravity, FEA + Sleeve Friction*, the deviations of the ENTHRU energy as function of the hammer parameters estimated as per Chapter 3 of this paper.
- *HVR PDA*, the PDA measurements “corrected” to account for the errors discussed in Chapter 2 of this paper. 5 blows at different impact energies have been “corrected” as shown in Fig. 9.
- *FEA*, showing the results of the FE calculations without accounting for the ring/sleeve interaction for the analysed 5 blows at different impact energies. It follows that these dots are all lying close to the line ‘FEA No Gravity’, as they should because no sleeve friction is included in the analysis.
- *Raw Data Check*, the raw data of the selected 5 blows at different impact energies used to compare

the HVR PDA and FEA results.

The Raw Data presented in Fig. 10 for the 4 measured monopiles, clearly shows instability of the ENTHRU energy at an impact energy of 1050 kJ. It further shows that, for impact energies larger than 1050 kJ, the actual ENTHRU energy is in general even lower than the estimated 'FEA + Sleeve Friction', which might be due to a sleeve friction larger than estimated.

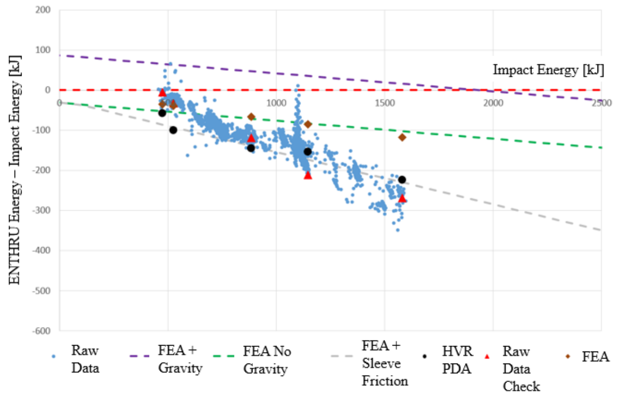

Fig. 10. Review of PDA measurements and comparisons.

From the comparison between HVR PDA, FEA and Raw Data Check for the selected blows it follows that higher values of the ENTHRU energy are calculated with "standard" FE analysis, as also mentioned in Chapter 3. From a comparison between the HVR PDA data and the Raw Data Check it also follows that the measurements "corrected" as per Chapter 2 are all close to the 'FEA + Sleeve Friction' line, indicating that sleeve friction is present for all these blows and that this friction is more or less constant relative to the impact energy. In general, correcting the PDA raw data to eliminate possible measurement errors provides better correlation with FE results in terms of ENTHRU energy when friction effects are accounted for in the numerical calculations.

5 CONCLUSIONS

In this paper, PDA data from a measurement campaign on large monopiles were used to discuss measurement errors, both related to signal acquisition and signal post-processing, that can affect the accuracy of the conclusions from such measurements, in particular when large monopiles for offshore wind farms are driven into the soil. By comparing PDA measurements and a large set of FE calculations, it was also possible to identify the effects of pile driving equipment on the ENTHRU energy, and therefore to determine correction methods to address the inaccuracy of the executed PDA measurements and the errors in the evaluation of the recorded measurements.

A critical review of the analysed measurements demonstrated that correcting PDA data to account for signal acquisition and processing errors, together with the effects of the pile driving equipment, will result in a better alignment between PDA and FE calculations, that can be considered reliable for ENTHRU energy estimations in case friction effects are accounted for in the numerical calculations.

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