Comparison of Three Different Methods for Pile Integrity Testing on a Cylindrical Homogeneous Polyamide Specimen

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Abstract. Three different methods for pile integrity testing are proposed to compare on a cylindrical homogeneous polyamide specimen. The methods are low strain pile integrity testing, multichannel pile integrity testing and testing with a shaker system. Since the low strain pile integrity testing is well-established and standardized method, the results from it are used as a reference for other two methods.

1. Introduction

The main method currently used for quality assurance of foundation piles is low strain pile integrity testing or PIT, which is well-established and standardized [1]. A pile head is hit with the hammer, what produces a stress wave travelling down to the pile toe and reflecting back to the pile head. The received wave is measured by an accelerometer mounted on the pile head. The length as well as the location of large flaws can be determined after the interpretation of the results [2,3]. Multichannel measurements approach was taken from geophysics, it is called "Ultraseismic" [4] or multichannel pile integrity testing [5], and the purpose of it is to improve the testing of the pile walls or piles under the structures (e.g. slabs, pile caps, etc.). As part of the PileInspect project, a shaker system instead of a hammer was offered to use, which allows not only performing repeatable measurements, but also enables a better controllability of the input signal [6, 7]. Furthermore, the use of higher frequencies may increase the resolution for the detection of smaller flaws.

Since the low strain pile integrity testing is well-established and standardized method, the results from it are used as a reference for the other two methods. All experiments were performed at Bundesanstalt für Materialforschung und -prüfung, Berlin, Germany. To compare three different methods a homogeneous material as polyamide has been chosen in the form of a 2 m long pole with 20 cm in a diameter.

2. Low strain pile integrity testing

The theory behind the PIT using a hammer was well described by Stahlmann et al. [8], where a compression stress wave induced by a hammer blow travels from the pile top downwards and reflects from the pile toe in regard with the impedance changes. The graphical representation of the results is a so-called reflectogram or a velocity-time plot. Thus, according to it one can estimate the length of the pile using the following expression [8]:

$$L = \frac{c \cdot t}{2},\qquad(1)$$

where c is the wave velocity and t is the travel time.

The test was carried out on the polyamide pole using the PET (Pile Echo Tester) device from the PileTest company [9], which is shown in figure 1.
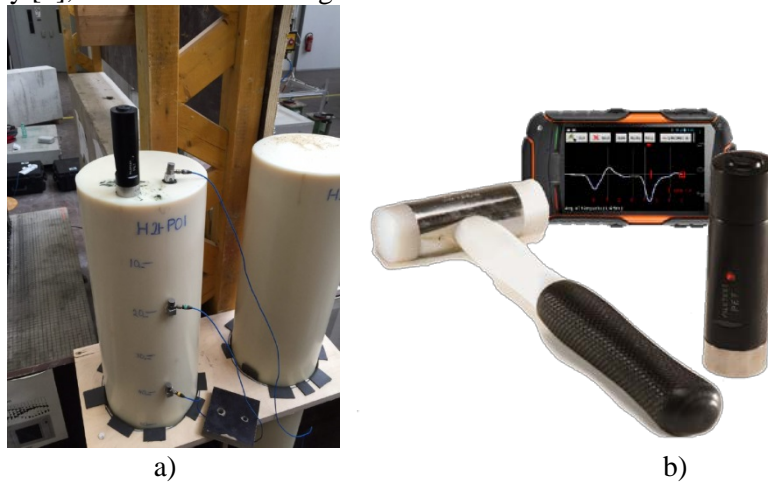

a)   b)
Figure 1. Experimental set-up for the PIT: a) the specimen, b) PET device (figure from [9]).

The corresponding reflectogram can be seen in figure 2. The aim is to adjust the velocity so, that the maximum of the second peak is positioned exactly at the line corresponding to the length of the pole, which is 2 m in our case. Thus, the resulting wave velocity is 1850 m/s.
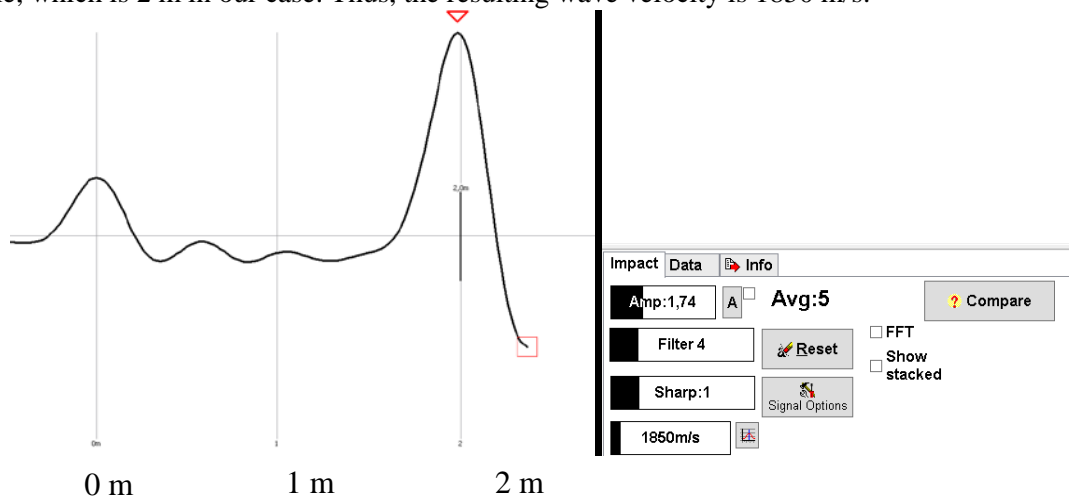

Figure 2. Results of the PIT using hammer on the polyamide pole.

3. Multichannel pile integrity testing
As it was mentioned above to improve the testing of the piles under the structure (e.g. slabs, pile caps, etc.) the multichannel pile integrity testing has been developed [4]. Basically, the classical PIT with the hammer blow was modified by increasing the amount of accelerometers, which are placed vertically along the pile shaft. The number of accelerometers depends on the accessibility of the pile, however, one can note that the method requires at least 1 to 1.8 m of exposed area to provide accurate field measurements (within 5% or better) [10].

The test was accomplished by using a hammer and 6 accelerometers, which were mounted each 20 cm, starting from the top (zero point) going down to 1 m. The signals from the accelerometers were collected by a data acquisition system (DAQ) with the sampling frequency of 51.2 kHz and sent to a field laptop. The whole system is shown in figure 3.
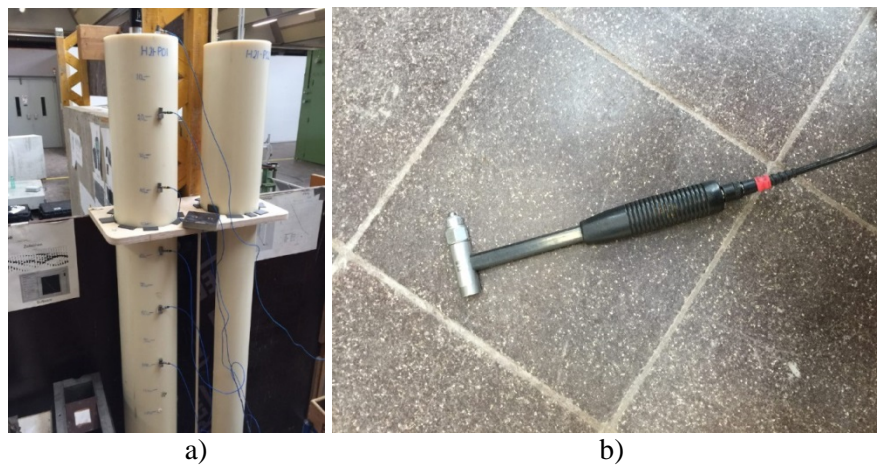
a)   b)

Figure 3. Experimental set-up for the multichannel pile integrity testing: a) the specimen with the sensors, b) the testing hammer.

The wave velocity can be determined using the slope (red line in figure 4), which corresponds to the time of the first wave arrivals at each accelerometer, the further away a sensor is the more time is needed for a wave to reach it. Also, the time values can be taken from the negative peaks, which indicate the wave passing the sensor location. The velocity is calculated at the time of first arrivals at 0.2 and 1 m sensors positions using following expression:

$$c = \frac{\Delta s}{\Delta t} = \frac{1m - 0.2m}{0.4189ms - (-0.002137)ms} = 1900 \frac{m}{s} \qquad (2)$$

Based on the velocity, now the length of the pole can be determined using the negative peaks of the accelerometer at the zero position as follows:

$$L = \frac{c \cdot \Delta t}{2} = 1900 \frac{m}{s} \cdot \frac{(2.4777ms - 0.2955ms)}{2} = 2.07m$$

This gives an error of 0.07 m, resulting in a percentage-wise error of 3.5 %. However this method allows the estimation of both the wave velocity and the length of a pile/pole, which is useful in practical applications, where the information about velocity is missing and has to be assumed.
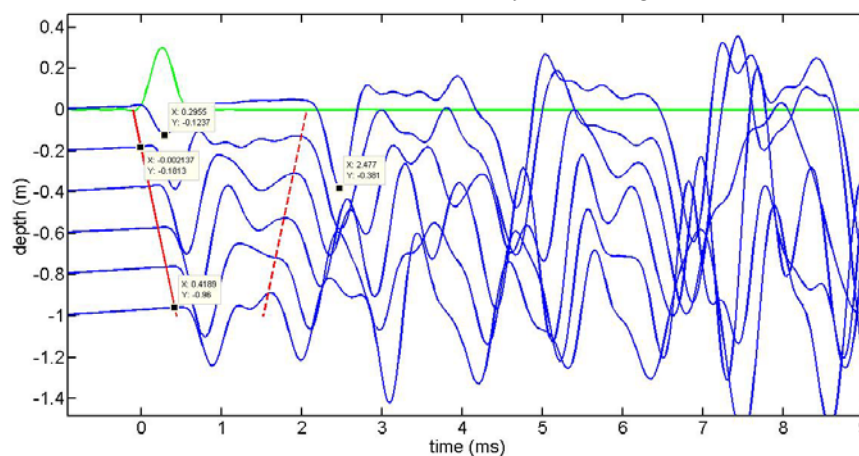

Figure 4. Result of multichannel measurement: green line – hammer blow signal; blue lines – received signals from accelerometers at corresponding depth; red line – first wave arrivals; red dashed line – the time arrivals from the toe reflection.

4. Testing with a shaker system

The idea of using the shaker (tactile transducer) as a source of the excitations was taken from Paquet and Briard (1976) [11] and suggested to use in the frame of PileInspect project, where the main motivation was not only the low cost and easy handling, but also the possibility to use new signal processing techniques on the data obtained. The theory, on which the data processing is based on, is described in [7] and it is suggested to use the impulse response function by performing the deconvolution of the recorded (output) signal with the excitation (input) signal. One of the important points to obtain the impulse response is that the deconvolution must be stabilized using the regularization factor (method after Tikhonov [12]):

$$I(\omega) = \frac{S(\omega)^{*} \cdot X(\omega)}{(S(\omega)^{*} \cdot S(\omega) + \lambda) \cdot dt}, \tag{3}$$

where $S(\omega)$ is the input of the signal's spectra, $X(\omega)$ is the recorded signal's spectra, * is complex conjugate of the spectrum, λ is the regularization factor and dt is the time increment of the measurement.

Then $I(\omega)$ is transformed into time domain to retrieve the impulse response $i(t)$.

The experiment was performed using a shaker, which was positioned on the pole top. The input signal was recorded with the low sensitive accelerometer of 10 mV/g, which was attached on the top of the shaker with some adhesive putty. The accelerometer, with the sensitivity of 100 mV/g on the top of the pole, was used to record the output signal. Figure 5 depicts the experimental set-up. The signals were generated and analysed using the software, designed earlier using LabVIEW specifically for this application. The input and output signals, as well as the result of the deconvolution using 500-1000 Hz logarithmic sweep with the length of 0.1 s are shown in figure 6.
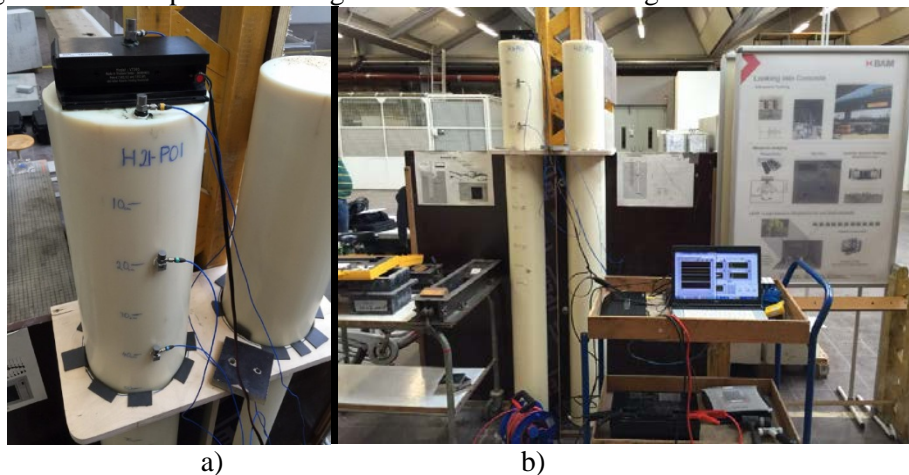

a)   b)

Figure 5. Experimental set-up for the testing with the shaker system: a) the specimen with the shaker and sensors, b) complete set-up.
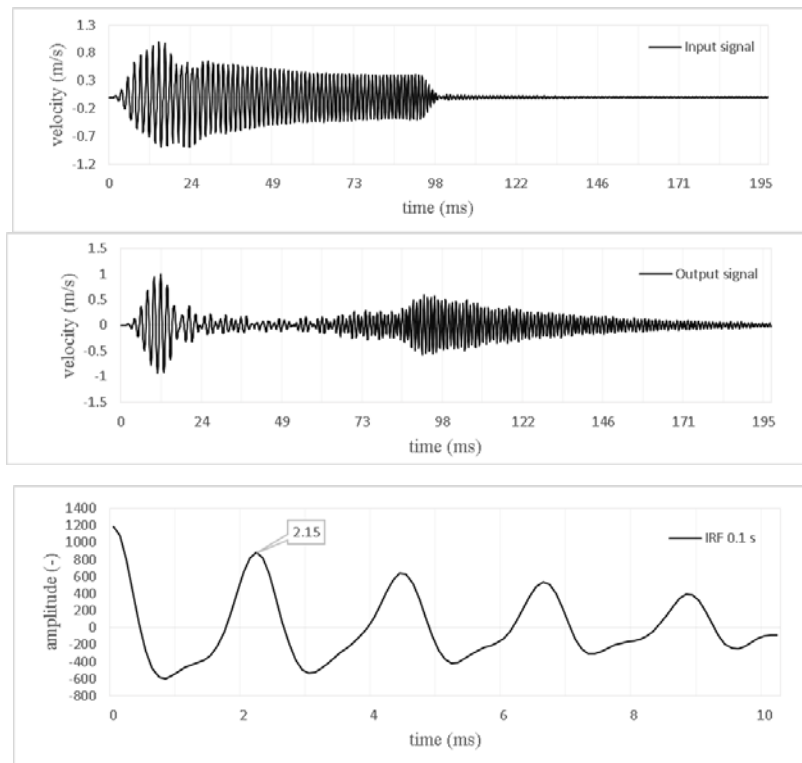
Figure 6. Results of the shaker experiment using a logarithmic sweep of 500–1000 Hz with the length of 0.1s.

Using expression (1) and the wave velocity of 1850 m/s obtained with PIT, the length of the pole can be calculated as follows:

$$L = 1850 \frac{m}{s} \cdot \frac{2.15 \cdot 10^{-3} s}{2} = 1.99 m,$$

which gives the percentage-wise error of 0.5%.

Also, for the same frequency range different sweep lengths were tested. The results, which are depicted in figure 6 were deconvolved and processed based on exp. (3) using the same regularization factor. It can be seen that the peak of the impulse response function (IRF) for the 1 s sweep length is slightly shifted to the right, compared with other two. So, for the time of 2.15 ms the corresponding length is 2.08 m, which gives the percentage-wise error of 4%.
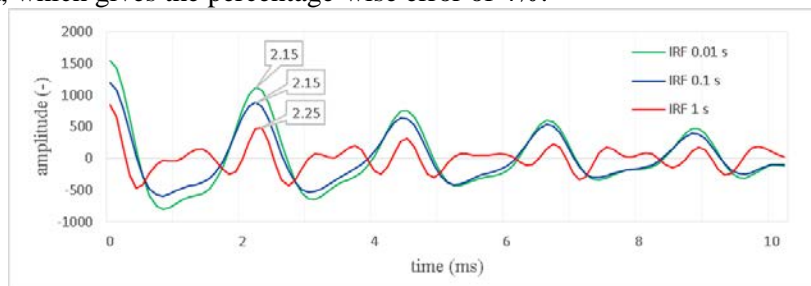

Figure 6. Comparison of the impulse response functions obtained by sweeps with different lengths.

5. Conclusion
Thus, the results show that it is possible to determine both the length of the pole and the velocity of the wave only by the multichannel pile integrity testing. For other two methods at least one parameter has

to be assumed. In practical applications, for instance, after the production of new piles, when the pile length is known, the velocity and the presence of flaws can be determined. In other cases, there is no information about the velocity and the length, and these parameters have to be assumed. All results are summarized in Table 1.

Table 1. Results of velocity/length determination using three different methods.

Method	Velocity (m/s)	Length (m)
PIT	1850	2
Multichannel testing	1900	2.07
Testing with shaker	taken from PIT	1.99 (2.08)

The velocity for the testing with the shaker system was taken from PIT results, due to the fact that this method is well-established and standardized. The different sweep lengths were tested and corresponding impulse response functions were compared (figure 6), the time value has a small deviation, which may indicate that sweep length shorter that 1 s gives more accurate results in length estimation. Also, different types of filtering and algorithms for the regularisation of the deconvolution may affect the results, thus the further investigations are needed.

6. Acknowledgements

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