

Defect Detection in Concrete Pile Using Impulse Response Measurements with Sine Sweep Excitations

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Abstract

For pile integrity inspection, a low cost and portable shaker was used to create the sine sweep signal for pile excitation. The impulse response function, calculated by the deconvolution of pile response from the sine sweep excitation, was proposed to identify the echoes in the piles due to the pile's impedance changes. The proposed methodology has been evaluated and validated both numerically and experimentally. Based on the results from the simulations and experiments, it was found that the impulse response measurement with sine sweep excitation could be an effective tool to detect the echoes of the pile toe and the defects in the pile.

Keywords: impulse response function, sine sweep excitation, pile integrity, damage detection

1. Introduction

The EU sponsored research project, PileInspect project, proposed the use of a low cost and portable shaker on the pile head to generate sine sweep excitation. The intention to use a shaker within PileInspect is based on the idea to use the highly innovative signal processing methodologies, in order to increase the diagnosis quality and perform automatic defect recognition [1]. In this study, it was proposed that the impulse response function is extracted by deconvolution of the pile response from a shaker's sine sweep. The echoes of the defects and the pile toe can be identified from the deconvolved waveform, i.e. the impulse response function. The pile response to a shaker's sine sweep excitation was simulated using a one dimensional (1D) pile-soil model. It was proved that the calculated impulse response function is effective to identify the echoes. Next, the proposed method was validated on the field test data. The pile tests were carried out at BAM test site [2]. The measurements from an intact pile and a defective pile were used for validation. In both cases, the reflection waves in the pile, i.e. the echoes from the pile toe and the defects, were effectively identified from the calculated impulse response function.

2. Simulation verifications

2.1 Impulse response function

In this study, the impulse response function of the pile-shaker system was used to interpret the reflection waves in the pile when subjected to sine sweep excitation. The impulse response function was calculated by deconvolution of the pile response with the shaker excitation [3]. Firstly, the system function was obtained by a spectra ratio in the frequency domain. Let u_p be the pile response, which was the velocity response of pile at pile top; and let u_s be the

shaker excitation, which was the velocity measurement on the shaker. The system transfer function could then be expressed as

$$H(\omega) = \frac{\hat{u}_p(\omega)\hat{u}_p^*(\omega)}{|\hat{u}_s(\omega)|^2 + \varepsilon} \dots\dots\dots (1)$$

where the hat symbol indicates the Fourier transform. The simple spectral ratio representation was unstable when the input spectrum was near to zero. For this reason, a regularization parameter ε was used to stabilize the deconvolution. The asterisk denotes the complex conjugate. By computing the inverse Fourier transform of the system transfer function $H(\omega)$, the impulse response function was obtained by

$$h(t) = FT^{-1}H(\omega) \dots\dots\dots (2)$$

where FT^{-1} indicates the inverse Fourier transform. The proposed pile integrity methodology based on the impulse response measurement is shown schematically in Figure 1:

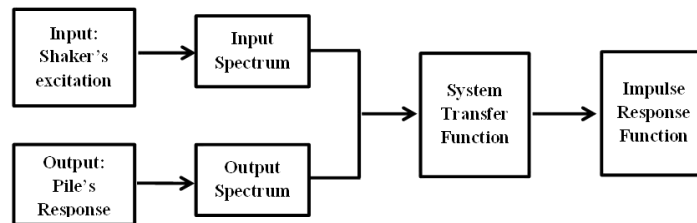


Figure 1. Schematic signal processing methodology of pile's impulse response function

2.2 Simulation results

To simulate the pile vibration responses to a shaker's sine sweep excitations, a one dimensional pile-soil interaction system was built and the finite difference method was used to calculate the pile responses. The reference intact pile has a length of $l = 12\text{m}$ and a circular cross-sectional area with a uniform diameter of $d = 0.8\text{m}$. The longitudinal wave propagation velocity of the concrete pile is $C = 3600\text{s/m}$. Theoretically the travel time of first reflection from the pile-toe can be derived: $2 * l/C = 6.7\text{ms}$. Two types of defective pile: a necking and a bulging in the pile are considered. As shown in Figure 2 (a), the locations of defects were both at the depths from 3m to 4m. At the necking defect, the diameter was decreased to 0.7m, while for the bulging the diameter was increased to 0.9m. Figure 2 (b) from top to bottom show the pile responses to sine sweep excitation, in the case of an intact pile, a pile with a necking and a pile with a bulging, respectively. Comparing the time domain records of pile responses, although there were minor variations in the waveforms, it was difficult to discriminate between the pile states whether 'intact' or 'defective'.

Following the signal processing procedure described in Figure 1, the impulse response functions were calculated for both the intact and defective piles. The sine sweep had a starting frequency of 100 Hz, an ending frequency of 1000 Hz and a duration of 0.1s. Figure 3 (a) gives the result of the intact pile and Figure 3 (b) gives the results of the defective piles with a necking and a bulging respectively. The reflection wave from the pile toe at 6.7ms can be identified in all cases, which matched with the theoretical value. For the defective piles, the reflection waves at the necking and the bulging had opposite phases. They both arrived at around 1.7ms, which was the travel time for the reflection wave at the depth of the first section of impedance change, i.e., 3m.

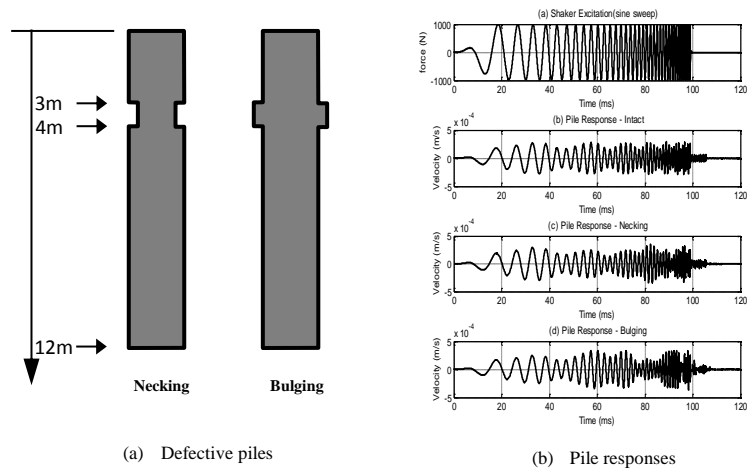


Figure 2. (a) Defective piles; (b) Pile response to sine sweep excitation (from top to bottom: sine sweep excitation; pile response – intact; pile response – necking; pile response – bulging)

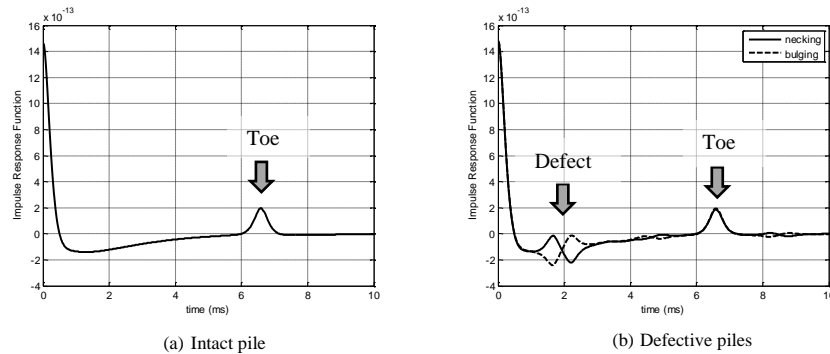


Figure 3. Impulse response function of pile response to sine sweep excitation

3. Experimental validations

To verify the proposed methodology, the impulse response functions were validated on the experimental data. The tested Piles were an intact pile P03 and a defective pile P06 at the BAM pile test site in Horstwalde, Germany. The results of traditional pile integrity tests (PIT) in 2012 are shown in Figure 4. Both of P03 and P06 have the length of 11m and longitudinal wave velocity of the pile, 4000m/s, which was identified in the previous study. According to the PIT results, the failure of P06 (horizontal cracks) was located in a depth of approximate 3.5m below the pile top.

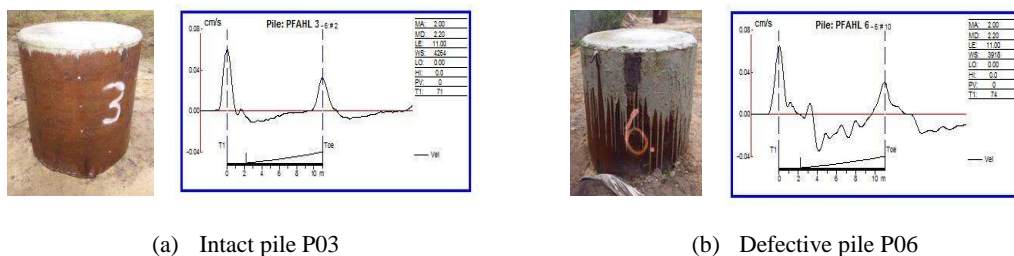


Figure 4. Test piles and pile integrity testing results

A variety of tests with different sweeps of various frequencies and periods were carried out. Figure 5 shows the example results of calculating impulse response function for P03 and P06 piles respectively. The sub-figures from top to bottom show the velocity waveforms of sensor

A0 and A1, and the resulted impulse response functions, respectively. The accelerometer A0 was mounted on the shaker and A1 on the pile top surface. The sine sweep signals had a starting frequency of 200Hz, an ending frequency of 1000 Hz. The durations of sweeps are 1 s. The regularization parameter was calculated by $\varepsilon = 0.005 * \max(|\hat{u}_s(\omega)|^2)$. The pile toe reflections arriving at around 5.5 ms can be seen in both piles, which are consistent with the PIT results. For the defective pile P06, an additional significant reflection can be seen at around 1.8 ms which corresponds to the depth of 3.6 m. This is a possible defect, which was found by the PIT testing in 2012, as shown in Figure 4 (b). But it should be noted that, during the recent standard PIT measurements on P06 in 2015, the fault zone is not very clearly visible. Hence, the further studies, both on shaker measurements and traditional PIT tests will be carried out in the next stage to investigate the actual condition of P06 pile.

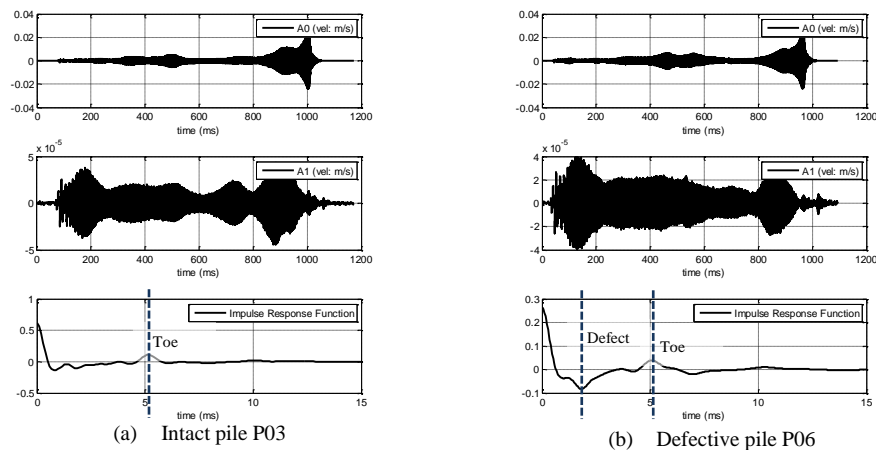


Figure 5. Impulse response function of test piles, [200 1000] Hz, duration of 1 s

4. Conclusion

Based on the results obtained from numerical verifications and experimental validations, it can be concluded that the impulse response measurement with shaker sine sweep excitation can be used as a novel, effective method for pile integrity testing. This technique offers the potential advantages in terms of repeatability and controllability on excitation amplitude and frequency compared with the traditional hand held hammer tool used in PIT.

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