Damage Detection of Concrete Piles Subject to Typical Damage Types based on Stress Wave Measurement Using Embedded Smart Aggregates Transducers

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Abstract

Concrete piles are the most common types of foundation structures. Pile damages, such as fractures, cracks, mud intrusion and secondary concrete pouring, are the leading causes of pile structural failure, which may directly result in casualties and economic loss. It is desirable to develop a monitoring system that can detect these pile damages. In this paper, embedded piezoceramic-based smart aggregates transducers along with the active sensing approach are developed to detect common types of pile damages, including crack, partial mud intrusion, secondary pouring, and full mud intrusion, based on stress wave measurement. With the active sensing approach, one smart aggregate is used as an actuator to generate a stress wave that will propagate along the pile, and other smart aggregate(s) will measure the propagating wave. All damages, which introduce new interfaces and discontinuities, attenuate the stress wave propagation. The attenuations of the stress waves based on different pile damages were compared by the received sensor signal in time domain. A wavelet packet-based energy analysis was used to develop an energy index to assist the detection of damages. Experimental results demonstrated the feasibility that the proposed approach can detect all four types of common damages associated with concrete piles.

Keywords: Pile; Pile damages; Damage detection; Smart Aggregate; Stress wave propagation; Piezoceramics

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1. Introduction

Building pile foundation not only transfers the load from the superstructure to the foundation but also enables the construction in very low bearing capacity soils and controls the soil settlement. The integrity of piles directly impacts the safety of the supported building structures. The inspection and testing methods of foundation piles have received considerable attention. The integrity testing of building foundation piles before construction acceptance inspection is a mandatory rule which was issued as a technical code. As we all know, Low-strain reflection wave testing (Rauschee et al 1992, Addison et al 1997, Likin et al 2000, Chow et al 2005, and Ding et al 2011) and cross hole sonic logging (Paikowsky et al 2000, Liet et al 2005, and Spruit et al 2013) are commonly used approaches to identify the integrity of foundation piles during daily construction work. Although these two approaches are proven techniques, they can only be used before the pouring of the concrete foundation beam. After all constructions have been completed, the health status of foundation piles, which are underground, will not be known. In recent years, optical fiber sensors are used for health monitoring of foundation piles as the frontier research (Liet et al 2004, Majumder et al 2008, and Lu et al 2012), however, as a limitation of fiber optic sensors, only local damage information can be provided.

Due to the special properties of dual capacity as a sensor and an actuator, high bandwidth, suitability for embedment, piezoceramic transducers have been researched in damage detection and structural health monitoring of concrete structure (Songet al 2005, 2006, 2007, 2008, Guet al 2006, Konget al 2013, Yan et al 2009, Xu et al 2013 and Feng et al. 2015). However, there are few reports on damage detection and health monitoring of foundation piles using embedded piezoceramic transducers. Songet al (2010) developed piezoceramic-based smart aggregates to detect the existence of crack in concrete piles with embedded smart aggregates at distributed locations. Wanget al (2013) demonstrated the proof-of-concept experiments with two bored piles using embedded piezoceramic transducers to detect pile with cracks based on the reference data from the intact pile. In the research of Songet al (2010) and Wanget al (2013), only the crack type of damage in piles was investigated. However, other type of damages, such as mud intrusion and secondary concrete pouring, were not reported.

In this paper, the piezoceramic-based smart aggregates, along with the active sensing approach and wavelet packet-based analysis, are used to detect concrete pile damages, including the previously unreported cases of mud intrusion and secondary concrete

1 pouring. With the active sensing approach, one smart aggregate is used as an actuator to
2 generate a stress wave that will propagate along the pile, and other smart aggregate(s) will
3 detect the propagating wave. All damages, which introduce new interfaces and discontinuities,
4 attenuate the stress wave propagation. A wavelet packet-based energy analysis was used to
5 develop an energy index to assist the detection of damages. Five concrete pile specimens,
6 including a health one and four damaged ones that respectively represent crack, partial mud
7 intrusion, secondary pouring, and full mud intrusion, were designed, fabricated, and tested in
8 this research. Experimental results demonstrated feasibility that the proposed approach can
9 detect all four types of common damages associated with concrete piles. This research
10 contributes to the development of an intelligent system that has the potential to realize
11 real-time monitoring of foundation piles during both construction and the service periods.

12 **2. Smart Aggregate Transducers and Active Sensing Approach**

13 **2.1 Smart aggregate Transducers**

14 Piezoelectricity includes direct piezoelectric effect and converse piezoelectric effect. When
15 the piezoelectric material is subject to a stress or strain, it will generate electric charge, which
16 is called the direct piezoelectric effect. The converse piezoelectric effect is the reversed
17 process to produce stress or strain due to the applied electric field. The PZT (Lead
18 Zirconate Titanate) is one of the most common used piezoelectric materials with a strong
19 piezoelectric effect. Since the PZT is fragile and has many limitations in field applications, a
20 smart aggregate is designed by sandwiching the waterproofed PZT with protection materials,
21 as shown in Figure 1. The diameter and the height of the smart aggregate is 25mm and 20mm,
22 respectively. The dimension of the PZT patch is 15mm×15mm×0.2mm (Kong et al 2013).
23 With the integrated piezoceramic patch, a smart aggregate transducer embedded in concrete
24 can function as an actuator to generate a stress wave or a sensor to detect a stress wave.

25

Figure 1: Smart aggregate (a) A photo of a smart aggregate with a connector (b) the schematic structure

2.2 Active sensing approach

Based on the piezoelectricity, smart aggregate can be utilized as both an actuator and a sensor. The active sensing approach can be simply illustrated by using two embedded smart aggregates with one as an actuator and the other one as a sensor. The smart aggregate as the actuator is connected to a waveform generator through a power amplifier. When the actuator is excited, it generates a stress wave, which propagates along the structure. At the meantime, the other smart aggregate as the sensor detects or measures the propagating stress wave. The strength of the received signal from the sensor is directly impacted by the conduit continuity of the stress wave propagation path. Therefore, this method can be developed to monitor the continuity of the stress wave propagation conduit, which can be a concrete pile.

3. Principle of Damage Detection of Concrete Piles

3.1 Stress wave energy attenuation through damage interfaces

A damage, if exists along the stress wave path, changes the continuity of the stress wave propagation conduit. The received stress wave energy will be attenuated associated with different damage interfaces. The schematics of stress wave propagation through different damage interfaces between embedded smart aggregates in concrete piles are shown in Figure 2. In Figure 2(a), no damage occurs along the stress wave path; In Figure 2(b), the partial mud is cross the stress wave path; In Figure 2(c), there is a secondary concrete pouring interface cross the stress wave path; In Figure 2(d), the crack is cross the stress wave path; In Figure 2(e), the full mud intrusion is just like a fractured interface cross the stress wave path. It can be seen that, when the excited stress waves are the same for each case, the smart aggregate sensor associated with the case of no damage can received the

1 most energy among others. Conversely, the sensor reports minimum energy in case of the
2 full mud intrusion which is a layer that can absorb most of the stress wave energy. The
3 received energy in other damage interfaces, including partial mud intrusion, secondary
4 concrete pouring, and the crack, highly depends on the actual condition of the damage
5 interfaces, such as location, dimension, shape, and etc. **It should be noted that the
6 effective distance of wave propagation using SAs is about 3 to 5 meters without an
7 amplifier. By using a power amplifier, the effective distance can be extended to
8 around 10 meters. In addition, for applications of large-scale concrete structures,
9 distributed SAs, as a sensor network, will be deployed, thus effectively linking
10 multiple SAs to cover the entire structure.**

11

12 Figure 2: Schematics of stress wave propagation through different damage interfaces(a): No damage along the
13 stress wave path; (b): the partial mud cross the stress wave path(c): the secondary concrete pouring interface
14 cross the stress wave path; (d)the crack cross the stress wave path (e): the full mud intrusionlike a fractured
15 interface cross the stress wave path.

16 **Typically, the most mechanical or structural background noise and ambient excitation**
17 **are in the low frequency range (<100 Hz). In the proposed active sensing approach, the**
18 **frequency range is in the relative high frequency range (100 Hz – 150 kHz). Therefore, a**
19 **high pass filter is implemented to minimize environmental noise and disturbance during**
20 **the measurement. If needed, a band pass filter with a passing frequency range (100 Hz –**
21 **150 kHz) can be also applied to reduce the effect of noise and disturbance in the lower**
22 **and higher frequency ranges.**

3.2 Wavelet packet-based energy analysis

As discussed above, when a guided stress wave propagates through a damage interface, the received signal energy will be attenuated based on the damage. Wavelet packet-based techniques have been utilized to detect the structural damage for many years (Sun et al 2002 and Song et al 2008). In this research, wavelet packet-based analysis can be utilized to compare the details of signal received from different damage interfaces. Based on the wavelet packet analysis, the stress wave energy can be computed as follows.

The sensor signal X is decomposed by n -level wavelet packet decomposition into 2^n signal sets $\{X_1, X_2, \dots, X_{2^n}\}$ (Song et al 2008). In each signal set X_j , where j is the frequency band ($j=1, 2, \dots, 2^n$), X_j can be expressed as,

$$X_j = [X_{j,1}, X_{j,2}, \dots, X_{j,m}],$$

where m is the number of sampling data.

The energy of each signal set can be computed as,

$$E_j = \sum_{k=1}^m X_{j,k}^2.$$

Therefore, the total energy of the signal can be computed by the summation of all the signal sets. The total energy of the signal can be computed as,

$$E = \sum_{l=1}^{2^n} E_l,$$

The wavelet packet-based energy analysis developed in this research provides a simple but effective way to obtain the energy value of the received signal. The wavelet packet-based energy values of signal received from different damage interfaces can be directly compared to each other.

4. Concrete Pile Specimens and Experimental setup

This section describes the concrete pile specimens that will be used to demonstrate the smart aggregate based active sensing approach for damage detection. In addition, the experimental setup that involves the data acquisition system will also be described.

4.1 Concrete Pile Specimens

Figure 4 shows the schematics of five concrete pile specimens. Please note that one has no damage and the other four have different artificially designed damages, which involve the partial mud intrusion, the secondary pouring interface, the circumferential crack, and the full

1 mud intrusion, respectively. To enable the active sensing approach, two smart aggregates
 2 were embedded in each specimen at pre-determined locations. A total of ten smart aggregates
 3 were used. The ten smart aggregates are sequentially numbered SA1 to SA10, as shown in
 4 Figure 4. Please note that along the path from SA1 to SA2, there is no damage. However,
 5 partial mud exists along the path from SA3 to SA4, a secondary concrete pouring interface
 6 exists along the path from SA5 to SA6, a circumferential crack exists along the path from
 7 SA7 to SA8, and a full mud intrusion that is like a fractured interface exists along the path
 8 from SA9 to SA10. Figure 5 depicts the cylindrical formwork prior to pouring the concrete. In
 9 each formwork, two smart aggregates with each being supported by a wooden stick can be
 10 clearly seen.

Figure 4 Schematics of the concrete pile specimens

Figure 5 Formworks with smart aggregates supported by wooden sticks

Figure 6 Concrete pile specimens with one undamaged pile and other four piles with different damage interfaces

4.2 Experimental Setup

Figure 7 shows experimental setup of the tests. The data acquisition system hosted by a laptop is used to generate the swept sine wave to smart aggregate actuators and receive detect signal from sensors. Please note that the signal was amplified by the power amplifier with a gain of 50. The sampling rate of the data acquisition system is 1MS/s. The detailed information of the swept sine wave signal is shown in Table 1.

Table 1: The detailed information of the swept sine wave signal before amplifier

Start frequency	Stop frequency	Period	Amplitude
100Hz	150kHz	1s	3V

Figure 7 Experimental setup

5. Experimental Results

5.1 Experimental Procedures

The experiments involve five separate tests of five pile specimens with different types of damages (Figure 6). For each set of tests, five experiments were conducted. 1) SA1 was used as an actuator and SA2 detected the wave response. Since there is no damage on the path from SA1 to SA2, this experimental data were used as the reference. 2) SA3 was used as an actuator and SA4 detected the wave response through the partial mud. 3) SA5 was used as an actuator and SA6 detected the wave response through the secondary pouring interface. 4) SA7 was used as an actuator and SA8 detected the wave response through the circumferential crack. 5) SA9 was used as an actuator and SA10 detected the wave response through the full mud intrusion. In all tests, the excitation signal is a sweep sine with a frequency spectrum of 100- 150K Hz. In this paper, data measured from the undamaged pile was used as reference, and the data measured from other damaged piles was compared to the reference data. Based on different damage types, the attenuation ratios in each case differ.

5.2 Damage Detection

The received signal of the five experiments are shown in Figures 8, 9, 10, 11, and 12. It can be clearly seen that the general signal strength in case of undamaged pile specimen, as shown in Figure 8, is greater than those four cases with different damage types, as shown in Figures 9, 10, 11, and 12. In addition, the lowest signal strength is also found in case of full mud intrusion. Since the damage interfaces attenuate the stress wave propagation energy, the general amplitude of the sensor signal received from undamaged pile is the greatest among others. Since the full mud intrusion, acting as a fractured interface in concrete, absorbed most of the stress wave energy, the corresponding sensor signal is the lowest. The signal strength from the other cases including partial mud intrusion, the secondary pouring interface, and circumferential crack, are not easily to be compared to each other in time domain, however, a detailed sensor signal energy can be presented using a wavelet packet-based energy index, which will be discussed in the next section.

Figure 8 Received signal of SA2 associated with the case of undamaged pile specimen

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Figure 9 Received signal of SA4 associated with the case of partial mud intrusion

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Figure 10 Received signal of SA6 associated with the case of secondary pouring interface

Figure 11 Received signal of SA8 associated with the case of circumferential crack

Figure 12 Received signal of SA10 associated with the case of full mud intrusion

5.3 Wavelet packet-based energy analysis

Figure 13 shows the energy indices of the sensor signal received from the five tests. It is clear that the energy index associated with the case of undamaged pile reports the highest level, the index value associated with the case of partial mud intrusion is greater than the one of secondary concrete pouring, the index value associated with the case of secondary concrete pouring is slightly greater than the one of circumferential crack, and the energy index associated with the case of full mud intrusion reports the lowest value. It can be seen that compared to the time domain analysis the wavelet packet-based energy indices give

detailed energy values which can be utilized to detect the different damage interfaces from concrete piles.

Figure 13 Energy indices for five experiments

5.4 Discussion – Stress wave attenuation based on different damage interfaces

Figure 13 shows the energy indices associated with different damage interfaces in concrete piles. There is no doubt that the lowest value of energy index is presented in the case of full mud intrusion, which is like a fractured interface and attenuates most of stress wave energy. For the other cases, including partial mud intrusion, secondary pouring interface, and circumferential crack, the values of energy indices depends to the actual conditions. In this paper, the order of the received signal energy from these three cases is partial mud intrusion, secondary pouring interface, and circumferential crack. However, other factors during construction, such as the dimension of the partial mud, the quality of secondary concrete pouring, the size of the crack, etc., can significantly affect the stress wave attenuation ratio and change the received signal energy. Therefore, the order of the energy values from those three cases may differ depends on the actual situations. **In addition, different pouring qualities will lead to differences in the concrete's properties, such as stiffness and damping, which will influence wave propagation. For this research, it is unlikely that the differences in concrete quality has overcome the signal change contributed by the damage.**

6. Conclusions

The proposed piezoceramic based active sensing approach was experimentally demonstrated to be a feasible approach to damage detection and identification of different damage degrees for concrete piles. A damage such as a crack, in a concrete pile structure, functions as a stress relief and attenuates stress wave energy, which can be utilized for damage detection using the active sensing approach. In the time domain analysis, from the amplitude of the received signals, we can clearly obtain the order which from the most attenuation to the least attenuation of the stress wave is as follows: fractured pile with full mud intrusion, cracked pile, pile with secondary concrete pouring, pile with partial mud intrusion, and undamaged pile. Such results are in good agreement with the signal energy values associated with the wavelet packet-based energy indices. In the future application of health monitoring, embedded smart aggregates can be used to monitor in real-time the health status of foundation piles during both building construction and service periods. **Moreover, installing SAs in existing concrete piles remains a future topic to study.**

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