Application of wavelet analysis for the impulse response of pile

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ABSTRACT

The purpose of this paper is to study the capabilities of the impulse response method in length and flaw detecting for concrete piles, and provide a suggested method to find small flaws in piles. In this work, wavelet transform is used to decompose the recorded time domain signal into a series of levels. These levels are narrowband, so the mix of different dominant bandwidths can be avoided. In this study, the impulse response method is used to analyze the signal obtained from the wavelet transform to improve the judgment of the flaw signal so as to detect the flaw location. This study provides a new way of thinking in non-destructive testing detection. The results show that the length of pile is easy to be detected in the traditional reflection time or frequency domain method. However, the small flaws within pile are difficult to be found using these methods. The proposed approach in this paper is able to greatly improve the results of small-size flaw detection within pile by reducing the effects of the noise and clarify the signal in the frequency domain.

Keywords: Pile, impulse response method, flaws detection, wavelet transform, non-destructive testing.

1. INTRODUCTION

The NDT methods for pile integrity testing can be classified into two main types, namely the surface reflection method and borehole method. In particular, sonic echo (SE) and impulse response (IR) methods, which are classified as surface reflection methods, have been used extensively to check the lengths and integrity of piles. It is more cost-effective than borehole methods. Among the related studies, only a few focus on the identifiable flaw in a pile and are summarized in Table 1. Of these studies, Kim et al. (2002) and Hartung et al. (1992) seem to provide the most systematic investigations on the surface reflection method. Based on the impulse response test, Kim et al. (2002) demonstrated that the flaw size should be at least greater than 50% to be detectable, while Finno and Gassman (1998) indicated that a 25% flaw size can also be detected successfully. When the sonic echo method was used for pile integrity detection, flaw sizes of more than 10% were indicated to be detectable in the research

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Table 1 Summary of publishe	d studies on the flaw de	etection in pile shafts u	sing surface
reflection methods			

Reference Flaw type		Model type	Flaw size (%)	Flaw depth ratio (diameter)	Analysis results
Baker et al. (1991)	Elliptical inclusion	Full size	15	2.9 (D = 0.9 m)	SE(N ^{*1}), IR(N)
	Elliptical inclusion	Full size	15	3.77 (D = 0.9 m)	SE(YN ^{*2}), IR(N)
	Necking	Full size	45	2.67 (D = 0.9 m)	SE(YN), IR(YN)
	Necking	Full size	45	13.11 (D = 0.9 m)	SE(YN), IR(Y ^{*3})
	Nonaxisymmetric void	Full size	50	13.11 (D = 0.9 m)	SE(YN), IR(Y)
Briaud et al. (2002)	Necking	Full size	45	5.46 (D = 0.92 m)	SE(Y), IR(Y)
	Necking	Full size	63	9.51 (D = 0.92 m)	SE(N), IR(YN)
	Necking	Full size	43	19.67 (D = 0.92 m)	SE(YN), IR(YN)
	Necking	Full size	50	3.28 (D = 0.92 m)	SE(YN), IR(YN)
Finno and Gassman (1998b)	Necking	Full size	25	4.13 (D = 0.91 m)	IR(Y)
Hartung et al. (1992)	Axisymmetric void	Model shafts	10-50	13.04 (D = 0.05 m)	SE(Y)
lskanker et al. (2003)	Necking	Full size	19	6 (D = 1.0 m)	SE(Y), IR(Y)
Kim et al. (2002)	Axisymmetric void	Model shafts	30-80	4 (D = 0.1 m)	SE(Y)
	Axisymmetric void	Model shafts	50-80	4 (D = 0.1 m)	IE(Y)
	Nonaxisymmetric void	Model shafts	30	6 (D = 0.1 m)	SE(Y), IR(YN)
Lin et al. (1991)	Axisymmetric void	FEM	75	5 (D = 0.4 m)	SE(Y), IR(Y)
	Central void	Full size	15	5.05 (D = 0.91 m)	IR(N)
	Necking	Full size	56	14.4 (D = 0.91 m)	IR(Y)
Sarhan et al. (2002)	Nonaxisymmetric void	Full size	10.67	2.8 (D = 0.762 m)	SE(N)
	Nonaxisymmetric void	Full size	14.4	3.0 (D = 0.762 m)	SE(Y)
	Nonaxisymmetric void	Full size	16.6	3.0 (D = 0.762 m)	SE(N)

^{*1}: no flaw was detected; ^{*2}: a flaw was possibly detected; ^{*3}: a flaw was detected

of Hartung et al. (1992). However, Lin et al. (1991) and Baker et al. (1991) show that a 15% flaw size is undetectable and Kim et al. (2002) show that a flaw can be detected by SE method when the size of it is larger than 30%. Obviously, an explicit limitation for both SE and IR methods in flaw size detection has not been unified in previous research.

From the above literature one can see that the surface reflected wave method can successfully be used to detect the flaw size in a pile, but the conclusions are not consistent. This result shows that, excluding testing personnel professional judgment, differences between the various experimental conditions, the position of pile defects, and relative stiffness of the surrounding soil are the most important influence factors. The amount of reflected wave energy will directly affect the result of surface reflection pile integrity assessment (Berger and Cotton, 1990; Stain, 1982). Therefore, these factors should not be considered separately. Huang et al. (2010) and Ni et al. (2011) used finite element simulation approach to discuss these factors, derived a formula that is able to determine the minimum detectable flaw size for the sonic echo and impulse response method. However, in practical in-situ tests, the results are not as good as expected (Huang, 2011). Because the limitation of signal analysis in often caused the error judgments (Ni et al., 2012), this study will use the discrete wavelet transform combined with the impulse response method to evaluate the defects in pile. The purpose of this paper is to investigate three different types of small-size defect (10%) cases in situ. The results of this paper would be compared to the results of sonic echo method. Factors that might affect the applicability of the surface reflection methods, including stiffness of the soil, type of mother wavelet, and the level of wavelet transform would not be covered and discussed in this paper.

2. SURFACE REFLECTION METHOD

The surface reflection method uses the wave reflected back from the location of the impedance change to evaluate the integrity of the piles. The sonic echo and impulse response methods are the two most popular ways for pile nondestructive tests due to the advantages of fast, economy, and wide ranges. The surface reflection method is done by introducing a transient wave into the piles by striking the pile head with an impulse hammer and records the vibration response of the piles by a geophone, which is also located on the top surface of the pile. The experimental schematic of the surface reflection method is shown in Fig. 1. The SE method interprets the transient response of the pile in time domain while the impulse response analyzes it in frequency domain. Details of these two methods are described in the following sections.

2.1. Sonic Echo Method

In the sonic echo method, one geophone is placed at the top surface of the pile head to record the transient response of the pile. The recorded signal is then processed to find the travelling time, phase direction and amplitude. The pile length (*L*) and the flaw depth (F_D) can then be determined by Eq. (1) and Eq. (2), respectively.

$$L = \frac{V_{rod}\Delta t_1}{2} \tag{1}$$

$$F_D = \frac{V_{rod}\Delta t_2}{2} \tag{2}$$

Where V_{rod} is the wave propagation velocity, Δt_1 and Δt_2 are the travelling times from the pile top to the pile bottom and back, and from the pile top to the flaw and back, respectively.



Fig. 1 Schematic depiction of the surface reflection method

2.2. Impulse Response Method

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With regard to the impulse response test, the impact force applied at the pile head should also be recorded. IR method converts the impact force and transient response into the frequency domain using Fast Fourier Transform (FFT) and then calculates the mobility, which is defined as the ratio of the velocity spectrum and the force spectrum. As shown in Fig. 2, to identify the repeated peaks in mobility curve is the key to successfully use the impulse response method to evaluate the pile integrity. Resolution of impulse response signals can be defined in terms of the ratio P/Q. The higher the P/Q ratio is, the higher the signal resolution is, and the easier to distinguish the resonant peaks. Thus makes it easier to determine the pile length and the location of flaws (Finno and Gassman, 1998a). The distance from the geophone to the source of the reflection (L_R) can be correlated with the frequency difference (Δf) between resonance peaks as shown below:

$$L_R = \frac{V_{rod}}{2\Delta f} \tag{3}$$

In previous studies, Δt and Δf are often assumptions so errors in locating defects and finding pile length are often arose. Therefore, in this study, use the relationship between Eq. (1) and Eq. (2), as shown below, is used

$$\Delta t = \frac{1}{\Delta f} \tag{4}$$

When the above equation condition is satisfied, the SE and IR methods would produce the same result. With the known pile length the wave propagation velocity can be back-calculated to be about 4000 m/sec. Also from Table 2, the general conditions of excellence are chosen because they are pre-cast piles, and the corresponding wave propagation velocity is about 4000 m/sec. Therefore, the wave propagation velocity of 4000 m/sec is used in this study.



Fig. 2 Typical mobility plot obtained from an impulse response test.

Table 2 Suggested	compression wave	e velocity	rating for	r concrete	from u	Itrasonic test	
	(From Malhoti	a, 1976,	Harrell ar	nd Stokoe,	1984)		

Compression wave velocity, m/sec (by Malhotra)	Compression wave velocity in a rod, m/sec (by Harrell and Stokoe)	General conditions
>4570	>4120	Excellent
3660 ~ 4570	3300 ~ 4120	Good
3050 ~ 3660	2750 ~ 3300	Questionable
2130 ~3050	1920 ~ 2750	Poor
< 2130	< 1920	Very poor

2.3. Discrete Wavelet Transform

One of the major advantages of using wavelet transform is that signal local features can be easily extracted. A wavelet is a waveform of limited duration that has an average value of zero. While Fourier transform breaks up signals into a series of sine-waves of various frequencies, wavelet transform breaks up a signal into shifted and scaled versions of the original wavelets. Two signals with the same spectral density could exhibit completely different transient characteristics (Newland, 1999). However, conventional Fourier analysis can only provide the spectral components of a signal and is independent of time. The scale (a) and shift (τ) parameters are the core of the wavelet transform and lead to the construction of the time-frequency information.

There are two types of wavelet transform: continuous wavelets transform (CWT) and discrete wavelets transform (DWT), and both are continuous in time. CWT

operates over every possible scale and translation whereas DWT use a specific subset of scale and translation values or representation grid (Addison, 2002). Wavelet coefficients, W_f , can be obtained by convoluting some proper wavelet function transform, $\psi(t)$, with input signal x(t) and is defined as follow

$$W_f(a,\tau) = \frac{1}{\sqrt{a}} \int x(t) \psi^*(\frac{t-\tau}{a}) dt$$
(5)

Where $\psi^*(t)$ is complex conjugate of $\psi(t)$. The above equation is called continuous or discrete wavelet transforms if τ and a are continuous, and discrete wavelet transforms if τ and a are discrete.

The drawback of the CWT is that the representation of the signal is often redundant, since *a* and τ are continuous over R (all real number). The original signal can be reconstructed completely by a sample version of $W_f(a,\tau)$. Sample $W_f(a,\tau)$ is in dyadic grid, i.e.,

 $a = 2^{-m}$ and $\tau = n2^{-m}$ $m, n \in \mathbb{Z}$ and $m, n \in (-\infty, \infty)$ And Eq. (5) can be rewritten as

$$W_{f}(m,n) = 2^{m/2} \int_{-\infty}^{\infty} x(t) \psi^{*}(2^{m}t - n) dt = \int_{-\infty}^{\infty} x(t) \psi^{*}_{m,n}(t) dt$$
(6)

Where $\Psi_{m,n}(t)$ is the dilated and translated version of the mother wavelet $\Psi(t)$.

Two orthogonal functions (scaling and wavelet functions) are used to decompose the frequency information into low and high frequency components in the wavelet transform. With the choice of a and τ , there exists the multiresolution analysis (MRA) algorithm, which decompose a signal into scales with different time and frequency resolution. MRA is designed to provide good time resolution and poor frequency resolution at high frequencies (through the wavelet function), and good frequency resolution and poor time resolution at low frequencies (through the scaling function). Therefore, the original signal can be separated into different frequency bands systematically.

A wave of any shape can be used as a mother wavelet if it is localized at a particular time. Several families such as Harr, Daubechies, Biorthogonal, Morlet and Mexican hat have been proven and widely used (Mallat, 1999). However, a universal criterion does not seem to exist for selecting an optimal wavelet function for a given application. In the following discussion, Daubechies wavelet family (dbN) is chosen to complete the analyses, and N is the order of the wavelet. These wavelets have no explicit expression except for db1, which is the Haar wavelet, and are compactly supported wavelets with extreme phase and highest number of vanishing moments for a given support width (Misiti et al, 2007).

A vanishing moment limits the wavelet's ability to represent polynomial behavior or information in a signal. For example, db1, with one moment, can easily encode polynomials of one coefficient, or constant signal components. db2 encodes polynomials with two coefficients, i.e. constant and linear signal components; and db3 encodes 3-polynomials, i.e. constant, linear and quadratic signal components. So, one can improve the multiple resolution of the signal by increasing the N value. db1 to db10 are the most commonly used. For the Daubechies orthogonal wavelets, the higher the

level is, the narrower the frequency bandwidth it can be decomposed to. Therefore, db10 is used in this study, and it can decompose the raw signal into 8 different frequency levels.

3. PILE INTEGRITY TEST PROCEDURE

The evaluation of pile integrity includes two major parts: the evaluation of pile length and the evaluation of defect location. The wavelet analysis for the impulse response of pile will be introduced to apply to the following two parts.

3.1 Evaluation of pile length

When determining the pile length using the impulse response method, the reflected signal from pile tip is usually interfere by high frequency noise. With the MRA characteristic of DWT, it can decompose the signal into multiple orders (layers), in this case, 8 layers, as shown in Fig. 3. The noise can be determine by transforming the layers of signals into frequency domain, and then find out the range of frequencies that are considered as noise, in this case this range is above 20 kHz, as shown in Figure 4(c). Moreover, the mechanical admittance curve is obtained by dividing the velocity spectrum (Fig. 4(c)) by force spectrum (Fig. 4(d)), so their range has to be the same. Fig. 4(c) shows that the frequency range of d1 and d2 (noise) falls between 20kHz and 50 kHz, and Fig. 4(d) shows that the frequency range falls between 0 kHz to 20 kHz. Therefore, this paper considers the signal to be noise if they are greater than 20 kHz. Layer d1 and d2 were then filtered out from the eight layers, the rest of the six layers were then stack back together to finish filtering, the result is shown in Fig. 4(b). Then, the impulse response method can be applied to the de-noised layer signal to determine pile length by finding periodically repeated peaks and finding frequency difference Δf . Finally, Eq. (3) is used to determine the estimated pile length.

The conventional impulse response method is already able to estimate the pile length up to 95% accuracy, which already satisfies the engineering requirement. The filtering does not affect the result too much, therefore, the accuracy of estimating the pile length will not be discussed in this paper.

3.2 Evaluation of pile flaws

Compare to using filtered signal to estimate pile length, to find defects on the pile is a lot more difficult. The wavelength of the impulse stress wave is usually too long that it will skip the defect, because most defects are small. Previous study states that the defects of area ratio under 10% are very difficult to detect because its reflected signal is too weak compare to the reflected signal from pile tip. This paper uses the MRA characteristic of DWT to decompose the signal using different scales into different layers, then, in each detail layer, the impulse response method is perform to analyze the signal.



Fig. 4 (a) Original signal (S) (b) De-noised signal (Ds) (c) Noise spectrum (d) Force spectrum

The defect signal is unidentifiable in raw time domain data. Through DWT decomposition, the decomposed signal can be divided into detail signal (dN) and approximating signal (aN), through wavelet function and scaling function, respectively. The letter N represents the level of decomposition. Signal in higher level has lower frequency. The approximation signal is the low frequency portion that looks similar to the original signal. Some of the lower level approximation signals (layers) are also eliminated because they are too similar to the original signal and are not likely to contain defect signal. From the previous section, layer d1 and d2 are eliminated because they are considered noise. Therefore, only layer d3 through d8 are consider the defect signal containing layers. The impulse response method is used to analyze these layers to estimate the location of defects.

4. TESTING EQUIPMENT

To obtain a high quality signal from the in-situ sonic echo test, an optimal configuration of hammer force source, a sensor and a signal capture facility are needed. A typical set of equipment is shown in Fig. 5. The equipment consists of a calibrated impulse hammer, geophone sensors, and a computer-controlled signal capturer (signal analyzer). The details of the equipment are listed below.

- 1. Sensor: The model-L28B Geophone (works as signal receiver), with natural frequency of 4.5 Hz, is produced by Mark Product, U.S.A. To ensure the geophone is in good contact with the top of the pile, gypsum is used as the bonding agent so that the stress waves can completely transmit to geophone.
- 2. Signal analyzer: The model HP35650A analyzer is a multi-tasking computer. The measurement hardware combined with the application software. The hardware capture signals both in time and frequency domains and the measurement data for a large number can be easily be configured. The sampling rate of the system is set to 102.4 kHz to make sure that the high frequency data won't be cut off.
- 3. Impulse hammer: The model-086D20 short-sledge impulse hammer made by PCB Piezotronics, Inc., USA, is used to create the pulse source. The hammer's resonant frequency is about 12 kHz, and the sensitivity is 0.23 mV/N.



Fig. 5 Test equipment

5. CASE STUDY

There are three precast hollow piles placing in the field beside the Department of Civil Engineering building in the National Cheng Kung University. All three hollow piles are 6 m long and have an outer-diameter of 30 cm and an inner-diameter of 17 cm. Defects of different types and shapes are pre-made on them for the purpose of this study. Pile no.1 has a 10 cm long circular necking at the depth of 5.1 m, and the area ratio of the necking is 30%. Pile no. 2 has two necks at depth of 3.3 m and 5.1 m, they have area ratio of 5% and 10%, respectively. Finally, pile no. 3 has two rectangular opening opposite to each other; the 7.4 cm by 15 cm opening on the top is 3.3 m deep, and the 22 cm by 15 cm one at the bottom is 5.1m deep. The detail dimensions of the piles and their defects are shown in Table 3.

The profile of the soil surrounding the piles is as follows: The depth from 0 m to 0.9 m is fills, depth from 0.9 m to 3.8 m is classified as SM, depth from 3.8 m to 6.3 m is classified as ML, and depth from 6.3 m to 13.6 m is classified as SM. There are three layers of soil surrounding the testing pile. The interfaces between each soil layer are located at depth of 0.9 m and 3.8 m.

Pile no.	Pile length (m)	Pile diameter (cm)		Flaw depth (m)	Flaw size (%)	Flaw type
1 6	6 Outer 30	5 1	20	Appular packing		
	0	Inner	17	5.1	30	Annular necking
2 6	Outer	30	3.3	5	Annular necking	
	2	0	Inner	17	5.1	20
3	6	Outer	30	3.3	10	Rectangular void
		Inner	17	5.1	30	Rectangular void

Table 3 Profiles of pile designed for the case study

5.1 Pile no. 1

The testing results of pile no. 1 are shown in Fig. 6. In comparing with the soil profile of the place, one can see that layer d3, d7 and d8 are of different confined condition, which means different soil layers, but the depth of the soil interfaces did not exactly coincide with boring log. There are two possible sources that might cause this error: from the signal itself or the slide inclination of the soil layers. Furthermore, the results show that the interface estimation of the shallow soil layer is more accurate than in deep soil layer, it is because the energy produce by the impulse hammer dissipated as it travels down along the pile. However, the pile tested is only 6 m long, so only the top two soil layers are considered in this study.

Layer d4, d5, and d6 are chosen to find the defect and its location. Because the results are very similar, the average value of the three layers is taken to perform the analysis. The estimated depth of defects from layer d4, d5, and d6 is found to be 5.22m, which has an error percentage of 2.4% comparing with the actual depth. This proves that DWT-based impulse response method is good for detecting defects that is larger than 30%.

It is interesting to notice that, in layer d3, d5, and d6, there are some peaks appear bedside the dominant frequency, and they are probably caused by the flexural vibration that is produced by the eccentric loading when the force is apply to the side of the pile

(Fei et al., 2007). According the study, this so call "bending vibration effect" can be minimized when the sensor and impulse source (where the hammer strikes the pile) from a 90 degree angle. Although the bending vibration effect can be minimized, it cannot be completely eliminated.

When finding the periodically repeated peaks in mobility curves, this study required three peaks to be chosen to ensure that these peaks are actually periodically repeated, and the error percentage of Δf of these three peaks have to be within 5%. Using this way, the chance of misinterpreting the data can be minimized.

Compare to the conventional impulse response method, which analysis the raw signal as a whole, the DWT-based impulse response method can provide an easier way of analyzing the data by decompose the signal into many layers.



Fig. 6 Frequency responses of different detail levels of the db10 in pile no. 1

5.2 Pile no. 2

In contrast to pile no. 1, which is the pile with only one large defect, the pile no. 2 has two smaller defects (5% and 20%) in different depth. There are two reasons why the pile in the pile no. 2 was designed this way: the first is to see if the DWT-based impulse response method is able to detect very small defects (5%), and the second is to test this method's ability to find multiple defects in one pile.

The testing result of the pile in pile no. 2 is shown in Fig. 7. Layer d3 indicates an impedance change at the depth of 3.12 m, which has an error percentage of 5.5% compare to the actual defect depth at 3.3 m. The results of layer d4, d5, and d6 are very similar, so an average value is calculated. The averaged result shows a defect at depth of 5.26 m, whit an error percentage of 3.1% compare to the actual defect depth of 5.1 m. Finally, layer d7 and d8 shows the interface of the two soil layers on the top, and the average depth is 1.13 m.



Fig. 7 Frequency response of different detail levels of the db10 in pile no. 2

The results in pile no. 2 are not as good for comparing with the results of pile no. 1, and the soil layer interface at depth of 3.8m cannot be found. The dissipation rate of the stress wave increased as the number of defects increased, so the reflected signal is not as strong and clear as in the pile no. 1.

The reflected signal from the small defect at depth of 3.3 m is weaker than the large defect at depth 5.1 m, so most of the MRA analysis methods can only pick up the reflected signal from large defects. However, the DWT-based impulse response method is able to extract the reflected signal from the small defect. This proves that this method can successfully reduce the influence of defect size to the estimation of defect location.

5.3 Pile no. 3

The defects of the pile in pile no. 3 are two square openings. They have the same depth as the circular necking in the pile no. 2, but the defect area ratios are increased to 10% and 30%. This case is designed to test the applicability of DWT-based impulse response method in detecting different defect forms. The test results of pile no. 3 are shown in Fig. 8.

As describe above, the results from layer d3, d5, and d8 are similar, so the average value of the three is used. The defect depth is estimated to be 5.20 m from the average of d3, d5 and d8, which has a 2% error percentage from the actual defect location. Layer d6 detects an impedance change at the depth of 3.39 m, and has a 2.7% error percentage from the actual 3.3 m deep defect. Finally, the average of layer d4 and d7 derives a depth of 1.02 m, which has a 13% error percentage from the interface depth (0.9 m) of soil layer.

The form and shapes of the defects does not affect the results too much, as one can see in this case. This means that DWT-based impulse response method is applicable to detect this kind of defect or abnormal condition of pile.

6. CONCLUDING REMARKS

The sonic echo and impulse response methods can successfully determine the length of the isolated piles. Testing results show that the sonic echo test is good to define the length of the pile, but it is not exact to define the defect location. The reason could be due to the defect location is placed too close to the bottom of the pile or the reflected signal is too small comparing with the signal reflected back from pile tip. Application of wavelet analysis with the impulse response signals can effectively separate noise, defect signal, and the signal reflected from the bottom of the testing pile. It is much easier to infer the defect location using the individual frequency plot from the decomposed signals. Wavelet transform-based impulse response method presented in this paper is able to estimate the pile length with percentage error less than 5%. This proves that the suggested method is an effective tool to determine pile length even if the piles are with small defects or existing significant soil interface.



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