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# Application of CCWT to evaluate the integrity of deep foundation

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## ABSTRACT

The purpose of this paper is to present an alternate signal processing approach to improve the evaluation of the integrity of pile foundation. This approach analyzes the amplitude and phase message of complex continuous wavelet transform from the data obtained from sonic echo testing data. It is much easy to determine pile length or defects of pile foundations by analyzing the time-frequency-phase angle diagram in different frequency band. Various piles were installed and tested to verify the proposed approach in this study. The results shows that complex continuous wavelet transform (CCWT) is able to not only provide high resolution results in different frequency bands but also simplifies the identification of the reflection of signals using 3D phase spectrogram. They are very helpful to insight into the integrity of deep foundation.

## 1. INTRODUCTION

There are many non-destructive techniques with signal processing methods that can be used to evaluate the pile length of an unknown pile foundation, such as the sonic echo (SE) method (Olson and Wright, 1989), the impulse response (IR) method (Davis 2003; Finno and Gassman, 2003; Hola and Schabowicz, 2010; Lin et al., 1991; Kim, 2002), a continuous wavelet transform (Ni et al., 2008),, the Hilbert-Huang transform (Bouden et al., 2012) , and the Wigner-Ville Distribution (Ni et al., 2007), etc., which are used mostly to determine the length or integrity of a pile (Ni, et al., 2008). It is not easy to find the length of the long pile by traditional reflection method and signal processing analysis due to the energy of reflected stress wave fades with the wave travel path during the testing. Ni et al. (2008, 2012) performed a series of tests using continuous wavelet transform (CWT) with piles that were not yet installed in soil, and the results were prominent. However, the method failed to detect the reflection signal from defects and pile tip after the piles were installed into the soil since the reflection signal becomes to be faded, especially for a long pile. Park and Kim (2001, 2006) used harmonic wavelet analysis of wave (HWAW) with SE method to find reflection signals of different mode numerically. Li, et al. (2007) used one-dimensional complex continuous

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wavelet transform (CCWT) to determine the pile length and defects. However, they did not look into the phase and lack more practical cases and details to verify the applicability of their method. Ni, et al. (2017) tried to use the phase relationship of signal from complex continuous wavelet transform (CCWT) to determine the pile defects. Ni, et al. (2017) also used the phase relationship of signal from complex continuous wavelet transform (CCWT) to determine the pile length.

The purpose of this paper is to provide case studies of a signal processing approach that determines the integrity of pile from the SE method by using the three-dimensional (3D) phase angle spectrogram obtained from the CCWT analysis. The CCWT is one type of wavelet signal processing technique. The CCWT was used to decompose a single time domain signal into several time domain signals of different frequencies. These decomposed time domain signals also contain phase angle information that allows one to determine the frequency of reflected wave amplitude to perform the phase angle viewing.

## 2. METHODOLOGY

### *2.1 Sonic Echo method*

The traditional SE test method provides a way to determine the pile length from reflection waves in piles. It determines the location of impedance change by finding the time difference between direct wave and reflection wave from impact pulse using its time history curve. The schematic drawing of this test is shown in 오류! 참조 원본을 찾을 수 없습니다..

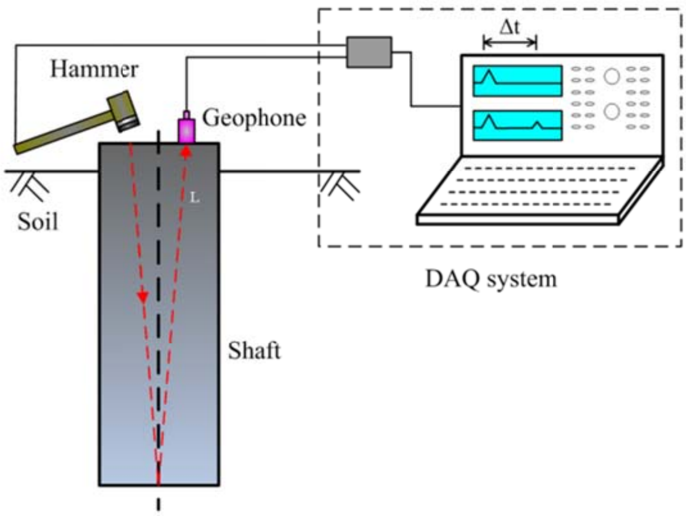


Fig. 1 Schematic drawing of a sonic echo pile test

In current practice, the low-strain integrity testing of foundation piles involves the interpretation of results from the SE method. The SE method has been widely used since it doesn't require any great amount of preparation or excessively expensive testing equipment. The technique is an example of impact hammer testing, where the response of a pile head to an instrumented hammer blow is measured while the movement of the pile head is recorded with an accelerometer (or geophone). The reflected wave/signal is the wave traveling from the pile head to the pile tip, which then reflects the pile head in the intact pile. In the case of known velocity, based on the one-dimensional wave propagation theory, the pile length can then be calculated by the travel time required for one round trip of a wave.

### 2.2 Complex Wavelet Transform

A wavelet transform analysis is a time-frequency analysis of a signal. It is widely used in different engineering fields. One major advantage provided by wavelet transform (WT) is the ability to perform a local analysis, i.e., to analyze only a section with a long duration signal. The WT method has been found particularly useful when analyzing periodic, noisy, intermittent, and transient signals.

Consider a real or complex-value continuous-time function $\psi(t)$ with two properties (Daubechies, 1992, Grossmann and Morlet, 1984). The function integrates to zero, and its square integral, or, equivalent, has finite energy. The function $\psi(t)$ is called a mother wavelet, or wavelet if it satisfies these two properties. Let $f(t)$ be any square integral function. The continuous wavelet transform (CWT) with respect to a wavelet $\psi(t)$ is defined as

$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t)\psi^*(\frac{t-b}{a})dt \tag{1}$$

Where *a* and *b* are real and * denotes the complex conjugate. The $\psi_{a,b}(t)$ is set as

$$\psi_{a,b}(t) = \frac{1}{\sqrt{|a|}}\psi^*\left(\frac{t-b}{a}\right) \tag{2}$$

Then, combining Equation (1) and (2), yields

$$W(a,b) = \int_{-\infty}^{+\infty} f(t)\psi_{a,b}(t)dt \tag{3}$$

Based on theory and a performance comparison, WTs based on several complex functions, e.g. Gaussian or Morlet functions, are suitable for signal analyses since they can achieve excellent time and frequency concentrations and are able to track the frequency trends at the local time better than other functions (Grossmann and Morlet, 1984). In this study, the complex Morlet functions will be used to analyze the signal obtained from SE test. The truncated complex Morlet function $\psi(t)$, as shown in Fig. 2, is given by the Matlab Wavelet-Toolbox (Misiti et al., 2015):

$$\psi^*_{a,b}(t) = \frac{1}{\sqrt{\pi f_b}} e^{2i\pi f_c t} e^{\frac{t^2}{f_b}} \tag{4}$$

Where $f_b$ is a bandwidth parameter. $f_c$ is a wavelet center frequency. The equation (3) can be written as $W(a,b) = \int f(t)\psi^*_{a,b}(t)dt$. Then, the instantaneous phase angle (*a, b*) of *W*(*a*, *b*) can be calculated as follows:

$$\phi(a,b) = \arctan\left(\frac{W_I(a,b)}{W_R(a,b)}\right), \tag{5}$$

Where $W_I(a, b)$ and $W_R(a, b)$ are the imaginary part and the real part of $W(a, b)$, respectively.

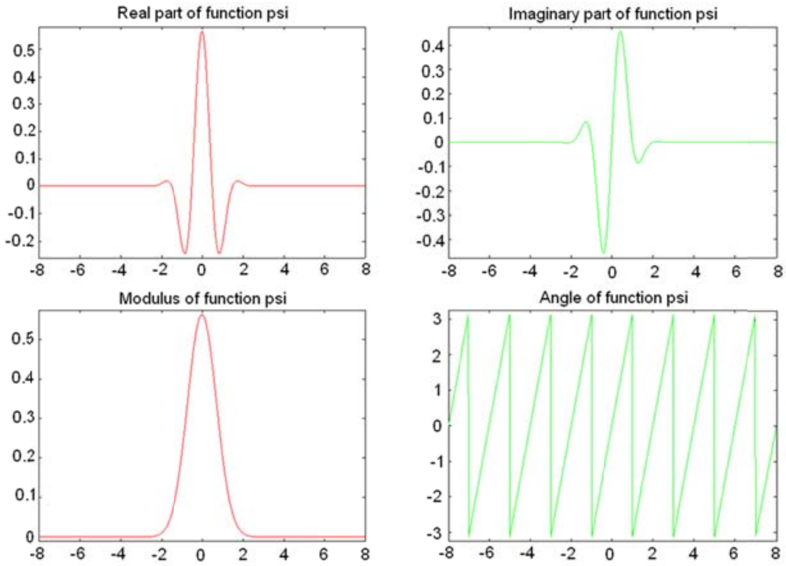


Fig. 1 Display of complex Morlet function ($f_b$=1, $f_c$=0.5)

From above equations, the CCWT uses two real wavelets in the real part and imaginary part to transform signals at the same time and then obtain the wavelet coefficients. The real part and imaginary part of a complex wavelet are orthogonal. In contrast to a real wavelet transform, which only obtains the signal amplitude in one space, the CCWT provides additional phase angle message in two orthogonal spaces. Then, the four basic figures, the real part, the imaginary part, the amplitude, and the phase angle are obtained with the CCWT, which is helpful to more accurately detect the signal.

The amplitude from wavelet transform is a magnitude of signal intensity which is proportional to the square root of reflected energy. When the structure has obvious interface or defects, the significant amplitude change of interface position is observed in the amplitude spectrum. The phase angle is a continuous measure in the phase angle spectrum. Its characteristic is regardless of the intensity of the reflected energy, the phase change can be displayed. It is a continuous phase angle if the wave propagation in an isotropic and homogeneous medium. In the case of abnormal position, there is a significant change in phase angle spectrum and its position can be determined.

In the complex Gaussian mother function figures described above, the maximum amplitude corresponds to the location where the phase angle is $-\pi$ to $\pi$. At this point, the local minimum real part and its corresponding imaginary part is 0. As the signal transforms with the mother function, when the wavelet coefficients and the mother wavelet results are in phase, the local maximum amplitude occurs at a phase angle –π to π.

## 3. TESTING MATERIAL AND EQUIPMENT

### *3.1 Testing Material*

Two six-meter-long precast hollow piles with outside diameters of 30 cm and inside diameters of 17 cm, and two long, drilled piles with the same diameters of 1.5 m and lengths of 34 m, and 53 m were verified by the in-situ SE testing with CCWT approach. The detailed information of these four piles is shown in Table 1. Pile A is a intact pile while pile C is with two man-made defects. The pile C has two 10 cm circular defects located 3.3 m and 5.1m from pile top. Their defected areas are 5% and 20%, respectively. The two different long piles, pile #1 and #2, were fully cased drilled piles constructed for a bridge foundation. The testing picture in the construction site for the drilled pile is shown in Fig. 3. Usually, each pile was hit three times. All measured signal responses of the geophone were stored in a computer. The signals were then analyzed using the CCWT method.

Fig. 3 Typical photo of in-situ SE test

Table 1 Characteristics of the drilled pile.

| Pile no. | Pile type | Velocity (m/s) | Pile length (m) | Pile diameter* (m) |
|---|---|---|---|---|
| PC-A | Precast hollow concrete pile | 4365** | 6 | Do = 0.3, Di = 0.18 |
| PC-C | Precast hollow concrete pile | 4282** | 6 | Do = 0.3, Di = 0.18 |
| #1 | drilled pile | 4000*** | 38 | 1.5 |
| #2 | drilled pile | 4000*** | 53 | 1.5 |

* - Do is outside diameter while Di is inside diameter.
** - Measured, *** - Assumed.

### *3.2 Testing Equipment*

In order to obtain high-quality signals for an in-situ sonic echo test, the optimal configuration of the hammer force source, sensor and signal capture facility are needed. A typical set of equipment is shown in Fig. 4. The equipment consists of an instrumented impact hammer, geophone sensors, and a computer-controlled signal capturer/analyzer. In this test program, a geophone with a natural frequency of 4.5 Hz was used. A dynamic signal analyzer was used to capture the signal. The impulse hammer with a weight of 22.3 N or 53.4 N (5 lbs o12 lbs) was used to create the pulse source. The transient force was applied to the surface of the pile head.


Fig. 4 Setup of equipment for the sonic echo test

## 4. ANALYSIS METHOD AND TEST RESULTS

### *4.1 Analysis Method*

As described in Section 2.1, the pile length L can be calculated from the time domain using the doubled travel time from the top to the bottom after the SE method is performed. However, if the CCWT in the time-frequency domain and the phase angle spectrum at the frequency corresponding to the maximum amplitude are used, the length of the pile (L) can be combined and written as following:

$$L = \frac{1}{2} \times c \times \Delta t \tag{6}$$

Where c is the wave velocity, $\Delta t$ is the double travel time from top to bottom, calculated from phase spectrum at the frequency corresponding to the maximum amplitude in the CCWT amplitude spectrogram.

To find the integrity of pile, the wavelet coefficient in the time-frequency domain of the signal is of interest. The variation of the coefficient indicates that the signal frequency content possible interface changed in some positions. Meanwhile, it could also be localized by the time history information. Usually, these discontinuities cannot be observed from an examination of the structural response in solely a time or frequency domain in a long pile because of the faint reflected energy. However, they are detectable from the distribution of the wavelet coefficients (or amplitude) obtained by the CCWT in the time-frequency domain and phase spectrum at the frequency corresponding to the maximum energy.

### *4.2 Test Results*

In time domain the echo signal is so weak that it is difficult to use the traditional time-domain analysis method to determine the arrival time or maximum amplitude of the reflected P-wave. In contrast, through the proposed method, the clear time position of reflected wave is obtained by applying the 3D amplitude spectrogram and the 3D phase angle spectrogram. Then, the length of the pile is calculated using the aforementioned steps.

<u>Pile A</u>

The typical time history signal obtained is shown in Fig. 5a and the suggested procedure to evaluate the length of the pile will be illustrated as follows. A three-dimensional time-frequency-amplitude diagram (simply called 3D amplitude spectrogram) need to be first plotted as shown in Fig. 5b and then the corresponding 3D phase angle spectrogram (the three-dimensional time-phase angle-frequency relationship) is plotted in Fig. 5c. The magnitude of the phase angle is presented in the manner of the gray level image. The white color is 180 degree ( of phase angle and black color is – 180 degree (- of phase angle in the gray level image of 3D phase angle spectrogram. Noting that the two energy concentration points are located at the shifting line of phase angle from πto-π in the 3D phase angle spectrum (see Fig. 5c). Variations in the phase angle with time (simply called a phase angle diagram) for the frequency corresponded to the maximum (or peak) amplitude are plotted in Fig. 5d.

As shown in Fig. 5c, the maximum amplitude of the pile head could be located about 1.8 msec while that of the tip location at about 4.6 msec. The reflection signal of the pile head and the tip were obvious. In addition, the main frequency bandwidth of the maximum amplitude value exists at about 928 Hz. The amplitude gradually decays from the lower to the higher frequency at the pile head and the pile tip.

Lines A and B shown in Fig. 5b are the lines passing the two energy concentration points. The travel time of wave ($\Delta t = t_{B\text{-line}} - t_{A\text{-line}} = 2.816$ ms) can be calculated from Figs. 5c or 5d. Time $t_{A\text{-line}}$ and time $t_{B\text{-line}}$ correspond to the locations of the time points along lines A and B in the phase angle diagram. The time between the two lines is the doubled travel time for the wave propagating from the pile top to the pile tip. The length of the pile could then be calculated with the known stress wave propagation speed, which was measured before the pile was installed in the ground. The length of the pile was calculated to be 6.15 meters using Eqn. (6) (i.e. L = 1/2*4365*2.816/1000 = 6.15 m). This result was very close to the true length of 6 meters.

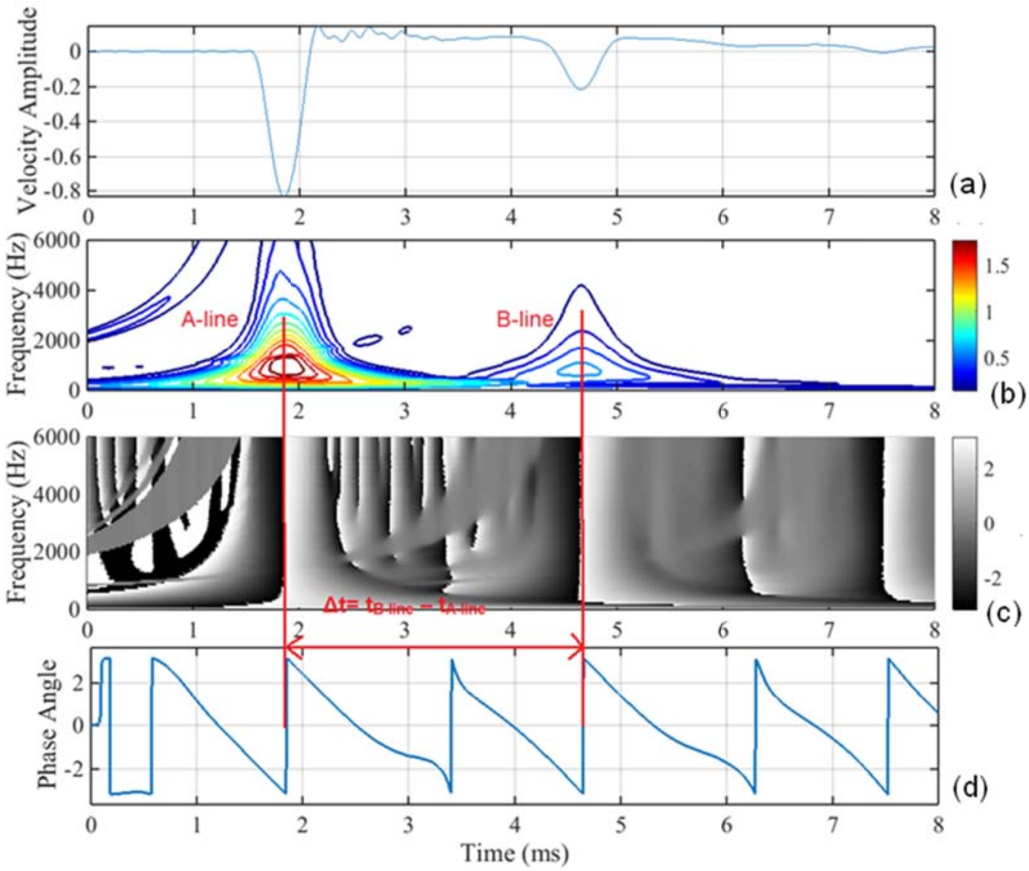


Fig. 5 Test result of a PC pile (a) Time history obtained from SE test (b) 3D amplitude spectrogram (c) 3D phase angle spectrogram (d) Variations in the phase angle with time at 928 Hz

Pile C

The test and analyzing the result of pile C is shown in Fig. 6. The length of the pile can be calculated from the time difference (the travel time of wave for a round trip) between point A and point B using equation (6). The length of pile is 5.88 meters using equation (14) for the travel time $\Delta t$ = 2.747 ms.

There are preset two defects in this pile. The specific frequency (976 Hz and 1584 Hz) of turning point D and F are selected to plot the phase diagram (see Fig. 6d and 6e). The locations of the defects can then be calculated from the time difference between maximum amplitude (MA) point K and inverting phase angle change (IPAC) point C(1.435 ms) and E(1.973 ms) using equation (6), respectively. The locations of defects are found at 3.07 m (i.e. L = 1/2*4282*1.435/1000 = 3.07 m) and 4.22 m (i.e. L = 1/2*4282*1.973/1000 = 4.22 m), respectively.

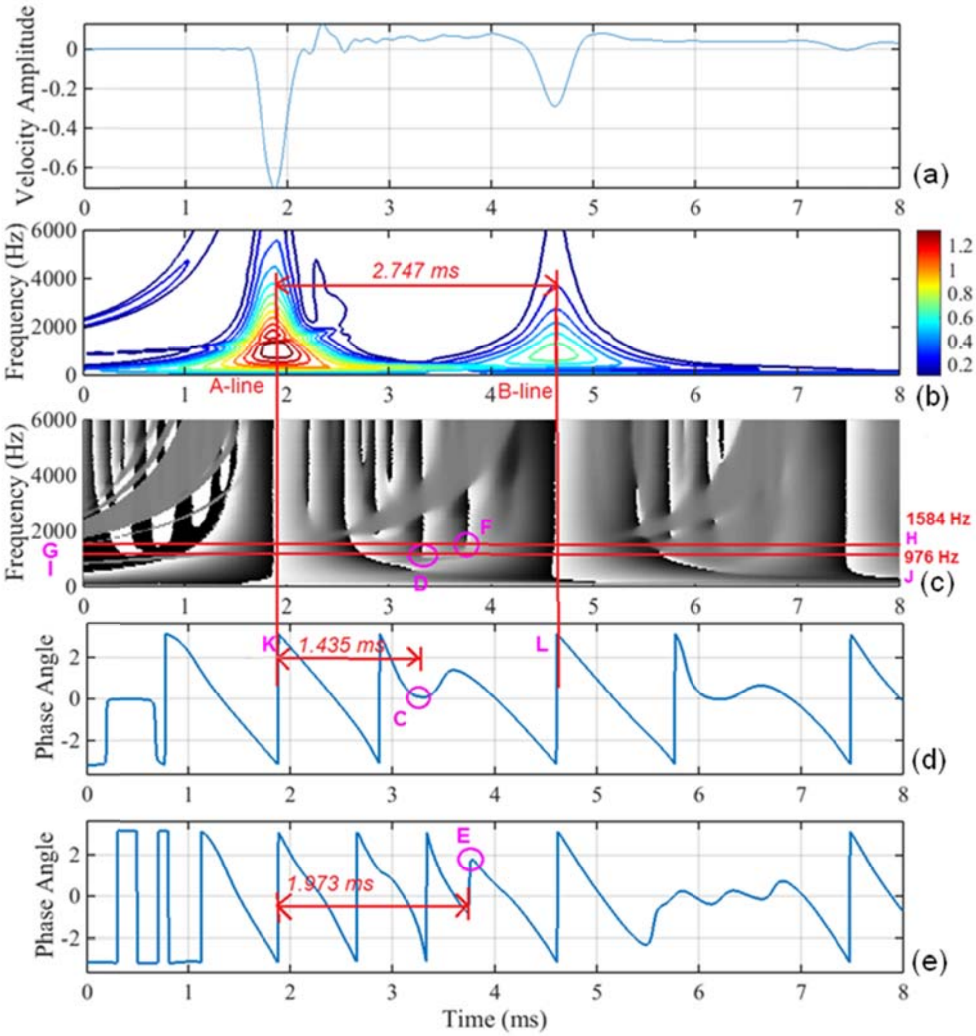


Fig. 6 Test result of pile no. C (a) Time history obtained from SE test (b) 3D amplitude spectrogram of test (c) 3D phase spectrogram of test (d) Variation of phase angle with time at 976 Hz (e) Variation of phase angle with time at 1584 Hz

<u>Pile #1</u>

The time history for Pile #1 obtained from the SE test is shown in Fig. 7a. When applying the CCWT, the incident wave from the pile top and the reflected wave from the pile bottom forms one energy concentration point in the 3D amplitude spectrogram, as shown in Fig. 7b. Its 3D phase angle spectrogram is plotted in Fig. 10c. Lines A and B are the lines passing – 180 degree (- of phase angle points shown in Fig. 7d. The doubled travel time of wave ($\Delta t = t_{B\text{-line}} - t_{A\text{-line}} = 18.80$ ms) can be obtained from Fig. 7d. The length of the pile is calculated to be 37.60 m (i.e. L = 1/2*4000*18.80/1000 m), which is very close to the design length of 38 meters.

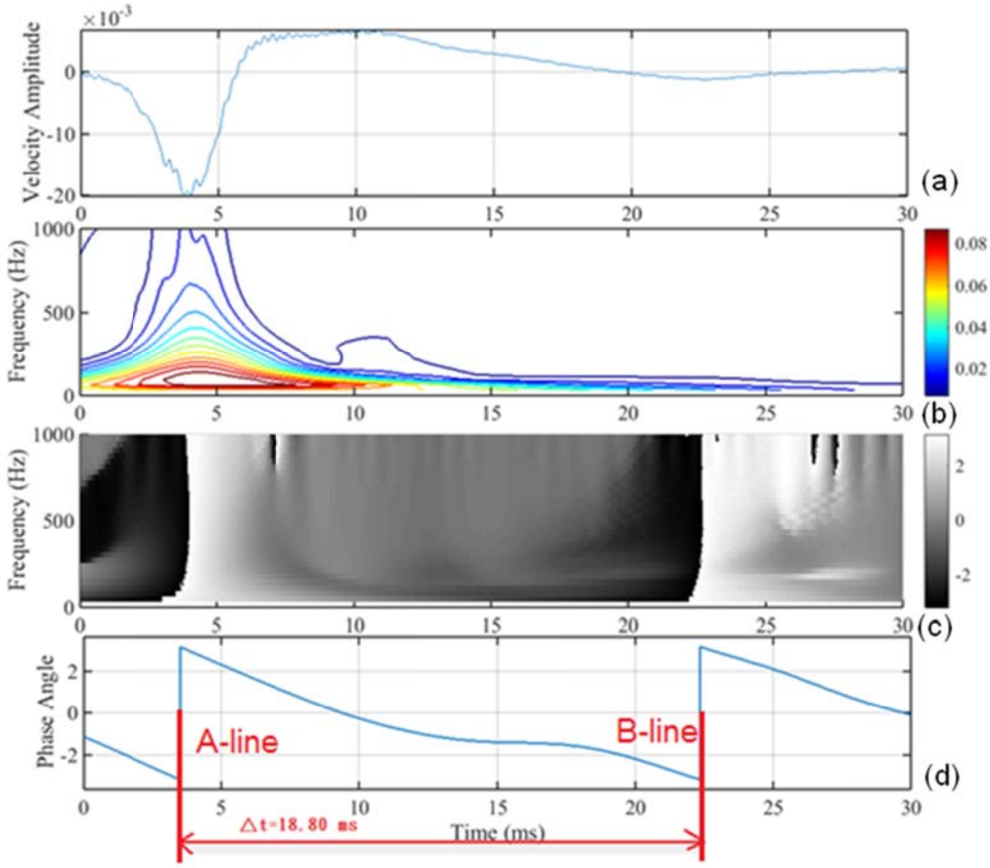


Fig. 7 Results of CCWT analysis of pile #1 (a) Time history obtained from SE test (b) 3D amplitude spectrogram (c) 3D phase angle spectrogram

<u>Pile #2</u>
The time history for Pile #2 obtained from the SE test is shown in Figure 8a. When applying the CCWT, the incident wave from the pile top and the reflected wave from the pile bottom forms one energy concentration point in the 3D amplitude spectrogram, as shown in Fig. 8b. Its 3D phase angle spectrogram is plotted in Fig. 8c. Line A is the line passing – 180 degree (- of phase angle points and Line B is the line passing 0 degree of phase angle (gravel layer) shown in Fig. 8d. The doubled travel time of wave ($\Delta t = t_{B\text{-}line} - t_{A\text{-}line} = 25.90$ ms) can be obtained from either Fig. 8c or Fig. 8d. The length of pile is calculated to be 51.80 m (i.e. L = 1/2*4000*25.90/1000 m), which is very close to the design length of 53 meters.

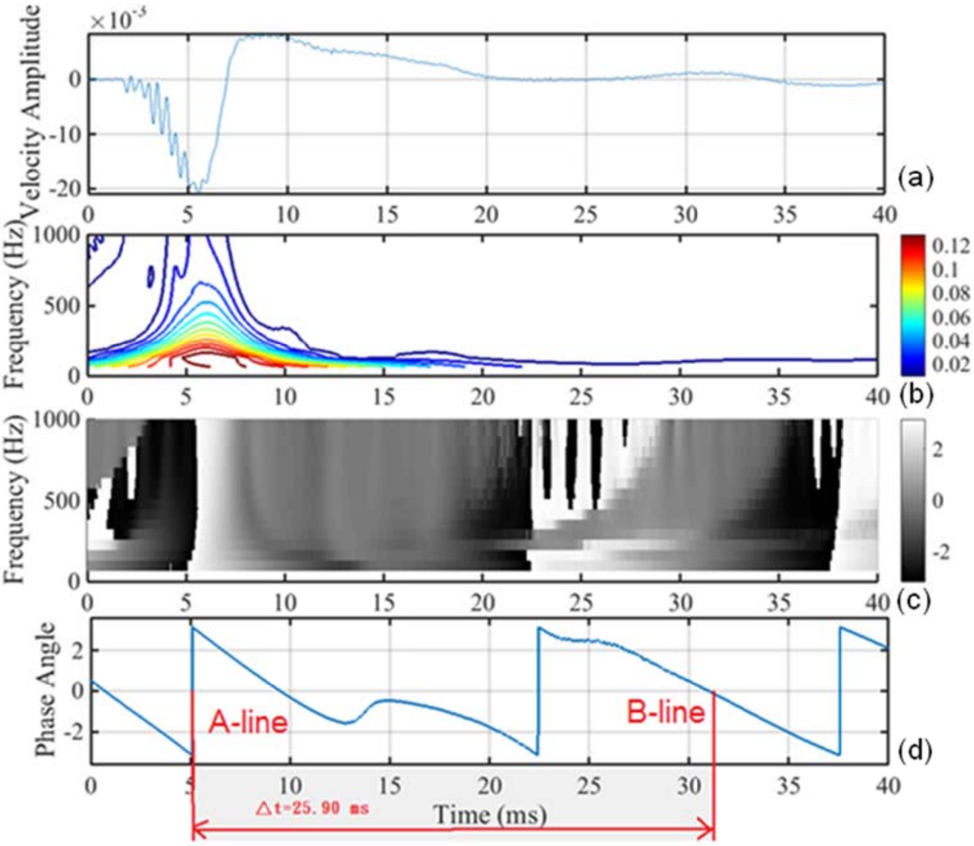


Fig. 8 Results of CCWT analysis of pile #2 (a) Time history obtained from SE test (b) 3D amplitude spectrogram (c) 3D phase angle spectrogram

The statistical results of the three piles are organized in Table 2. As shown in the table, the errors of pile length are within 3%. Its coefficient of variation is about 0.4% or less, so the dispersion of data is small and the resulting accuracy is good. This result represents that the accuracy and consistency of pile length are not affected by the pile with some defects or the increase of pile length. The results obtained are good for the general purpose of engineering. Moreover, the length of constructed pile may differ from designed length due to the error of wave velocity assumed of the pile. These reasons may cause the errors in the evaluation of the true pile length.

Table 2 Pile lengths and flaws evaluated and errors comparing with those designed

| Pile no. | Pile Length (m) | Error (%) | Flaw Location (m) | Error (%) |
|---|---|---|---|---|
| A | 6.15 | 2.50 | NA | NA |
| #1 | 37.60 | -1.10 | NA | NA |
| #2 | 51.80 | -2.26 | NA | NA |
| C | 5.88 | -2.00 | 3.07 | -7.0 |
| | | | 4.22 | -17.2 |

## 5. CONCLUSIONS

The following conclusions can be drawn from this case study.

1. The errors of pile length evaluation are within 2.5%.
2. The locations of deflect can be identified using time difference in phase diagram, and the errors are within 17.2%.
3. The suitability and applicability of this CCWT approach are verified by the in-situ testing of two six-meter-long precast hollow piles, and two long, drilled piles with lengths of 34 m, and 53 m, respectively.
4. The advantage of this approach is that even a weak and faintly reflected wave from the pile tip of a long pile can be easily identified using the time difference in the 3D phase angle spectrogram which is a superior as compared to the traditional SE method, IR method, or other 3D imaging methods.
5. It can reduce the man-made error, and it improves the accuracy of determination of the length of the pile.

## 6. ACKNOWLEDGEMENTS

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