Assessment of the Integrity of Piles by Impedance Log Technique

Jiunnren Lai¹, Chih-Peng Yu¹ and Shu-Tao Liao²

¹Chaoyang Univ. of Tech., 168 Gifeng E. Rd., Wufeng, Taichung County, Taiwan
²Chunghwa Univ., 707, Sec.2, WuFu Rd., Hsinchu, Taiwan

¹jlai@cyut.edu.tw, ²cpyu@cyut.edu.tw, ³shutao@ccu.edu.tw

Keywords: Integrity, Piles, Impedance, Stress wave.

Abstract. The objective of this paper is to investigate the capabilities of the Impedance Log (IL) method in profiling the geometry of a pile along its length. The main idea of this method is to introduce a transient stress wave into the pile and then utilize the reflected signals to obtain the impedance profile of the pile. The impedance profile can then be used to recover the cross-sectional profile (or material property) along the length of the pile. Any anomaly, which results in changes in impedance, would be detected by this method.

To gain an insight into the Impedance Log nondestructive evaluation technique, this paper starts with reviewing its theoretical background. A numerical program was developed to convert the time domain velocity waveform recorded at pile head into the impedance profile of the pile. Four model piles with plan defects of weak zones and necks were constructed and tested. Results of these tests show that interpretation of signals using the proposed method is more straightforward than the other traditional methods such as the Sonic Echo method or the Impulse Response method. It is concluded that the Impedance Log method is a tool with high potential for evaluating the integrity of piles.

Introduction

Evaluating the integrity of drilled shafts or driven piles has long been recognized as an important means for quality control in the construction industry [1]. For this purpose, several nondestructive testing techniques such as the Impact Echo (IE) [2], the Impulse Response (IR) [3,4], the Sonic Echo (SE) [5], the Cross-hole Sonic Logging (CSL) [1], and the Parallel Seismic (PS) [6] methods have been developed to access the integrity of piles. These methods were usually classified into two groups, surface reflection and direct transmission methods. Surface reflection methods are usually more economic, but they are unable to provide a complete picture of a pile with multiple defects. Direct transmission methods may diagnose a pile through its length in a more detail yet also more expensive way.

Of the NDE methods mentioned above, the SE and IR methods are of particular interest here because of their close relationship with the Impedance Log method. As shown schematically in Fig. 1, both methods involve impacting the top of a pile with a hammer to introduce a downward traveling transient stress wave. When the stress wave reaches a defect, such as a neck or a bulge, or the bottom of the pile, it will be reflected back to the pile head and can be recorded by a receiver. The SE method requires only the particle response history to perform integrity analysis. An idealized velocity waveform of a pile containing a bulge and a neck is illustrated in Fig. 2, stress waves reflected from the defects or the bottom of the pile can easily be identified.
For the IR method, the impact force and the particle velocity response must be both measured versus time on the impacted surface. These two time histories are then transformed to the frequency domain using the Fast Fourier Transform (FFT). The mechanical admittance (or mobility) of the pile is defined as the ratio of the amplitudes of the particle velocity and the force in the frequency domain. From the repeated pattern in the mobility curve (Fig. 3) one can usually find the existence of defects or bottom [7].

In the last decade, a relatively new method for evaluating the integrity of piles, the Impedance Log (IL) method was proposed and briefly described by Paquet [8,9]. The reported main capability of this method is to recover the changes of the cross-sectional area of the pile by obtaining its impedance as a function of the distance from the pile head. In other words, the method provides the geometric profile of the pile and its variation with depth. This is indeed the major purpose that a nondestructive testing technique for piles is intended to achieve. However, research results related to this method, either of a theoretical or an experimental nature [10], are still scarce.

**Theoretical Background of the IL Method**

Referring to Fig. 4, the procedures for application of the IL method can be summarized as follows [8]:

1. Perform the Impulse Response test on the pile to be evaluated. Use the particle velocity response and the force functions in the frequency domain, \( V_1( f ) \) and \( F_1( f ) \), to obtain the mobility curve of this target pile, as denoted by \( V_1( f ) / F_1( f ) \).
2. Generate the theoretical mobility curve of a fictitious pile, which has the same nominal diameter and same geometric configuration as the target pile but is defect-free and infinitely long. This curve is denoted by \( V_2( f ) / F_2( f ) \).
3. A new mobility curve, \( V_3( f ) / F_3( f ) \), that contains only the effect of reflections from defects and from the end of the shaft, can then be obtained by subtracting the experimental and theoretical mobility functions:

\[
V_3( f ) / F_3( f ) = V_1( f ) / F_1( f ) - V_2( f ) / F_2( f )
\]  

4. Perform the inverse FFT on \( V_3( f ) / F_3( f ) \) to obtain the relative reflectogram \( X(t) \) in the time domain. The relative reflectogram is then scaled to get the reflection coefficient, \( r(t) \). The impedance of the pile, as a function of time, can then be determined through

\[
Z(t) = Z_0 \exp \left[ 2 \int_0^t r(\tau) \, d\tau \right]
\]
where \( Z_0 = \frac{E_0 A_0}{C_p} \) is the impedance at the pile head, \( E_0 \) and \( A_0 \) are Young’s modulus and the cross-sectional area of the pile, and \( C_p \) is the wave propagation velocity in the pile.

(5) Finally the time function of the impedance \( Z(t) \) can be converted to the space function \( Z(x) \) using the equation \( x = C_p \times t \), where \( x \) is the distance measured from the pile head. The cross-sectional area of the pile at any distance from the top can thus be recovered using the impedance function \( Z(x) \).

Earlier work [11] had concluded that where a free-end boundary condition is encountered, the amplitude of the recorded response is actually twice that of the reflected wave. In this case, Eq. 2 should be further modified to be:

\[
Z(t) = Z_0 \exp\left[ \int_0^t r(\tau) d\tau \right]
\]

The normalized reflection coefficient \( r(t) \) can be obtained from the following equation:

\[
r(t) \approx \left( \frac{Z_o}{p_o A_m} \right) v_R(t)
\]

Where \( p_o A_m \) is the area of the fictitious impulse, and \( v_R(t) \) can be estimated from the velocity time history recorded in the SE method or from the mobility data computed in the IR method.

Based on Eqs. 3 and 4, a numerical program was developed to convert the time domain velocity waveform recorded at pile head into the impedance profile of the pile. Comparison between results of these three NDT pile integrity testing methods will be discussed in the following sections.

**Testing Program**

As shown schematically in Fig. 5, four 3 meters long, 0.3-m in diameter concrete model piles were constructed for this study. Among these four piles, pile P1 is an intact pile. Pile P2 contains a 10cm-long, 2-cm deep necking (about 25% cross-sectional area reduction), at a distance of 1.2 meter below the pile head. Pile P3 contains a 10-cm-thick weak zone (compressive wave velocity, \( C_p \), of this poor quality concrete is about 80% of the normal value) also at 1.2 meter below the pile head. Pile P4 contains two 10cm-long necking defects. The first necking has 25% cross-sectional area reduction, while the cross-sectional area reduction of the second necking is about 36%.

![Fig. 5 Schematic drawing of model piles tested in this paper](image-url)
All these four model piles were tested using the SE, IR, and IL nondestructive testing techniques. Results of these tests will be discussed in the next section.

Test Results

**Sonic Echo Method.** The velocity waveforms recorded at the head of the four model piles from the SE test are shown in Figs. 6a - 6d. For the intact pile (P1), the stress wave reflected from the bottom of the pile (circled in Fig. 6a) can easily be identified. For the two model piles contain single defect (P2 and P3), signal reflected from the defect (boxed in Figs. 6b and 6c), as well as signal reflected from the bottom (circled) can both be identified. However, there are also reflected signals, shown as question mark in Figs. 6b and 6c, maybe misidentified as defects. On the other hand, for the pile contains double necking defects (P4), only the signal reflected from the bottom of the pile can be identified. Signals reflected from the two defects were all mixed together, thus increase the difficulty in identifying them (Fig. 6d).

**Impulse Response Method.** The mobility spectra of the four model piles from the IR test are shown in Figs. 7a to 7d, respectively. For the intact pile (P1), the periodical event of stress wave reflected from the bottom can be seen as shown in Fig. 7a. For the two piles contain single defect (P2 and P3), both the periodical events of defect and bottom can be seen (Fig. 7b and 7c). For the double necking pile (P4), only the periodical events of the bottom and the first necking defect can be identified as shown in Fig. 7d. It should be noted that identification of these periodical events requires some experience with the IR test. Furthermore, the IR method and the SE method can only obtain information about the location of a defect, but not the magnitude of the defect.

**Impedance Log Method.** The Impedance profiles of the four model piles from the IL test are shown in Figs. 8a to 8d. For the intact pile P1, the IL method can obtain the exact profile of this model pile (Fig. 8a). For piles P2 and P3 that contain single defect, except for a little lag, the impedance profiles from the IL test are very similar to the actual geometry of the two piles (Figs. 8b and 8c). Even for the pile with double necking defects (P4), the impedance profiles from the IL test are still very close to the actual geometry except for the little delay. Furthermore, the magnitude of defect, express in the form of change in impedance can also be determined by the IL method. In comparison to the other
two traditional pile integrity testing methods such as the SE method and the IR method mentioned above, interpretation of the test results is much straightforward and requires less experience, especially for piles with multiple defects.

**Summary and Conclusion**

In this paper the theoretical background for the Impedance Log method was first presented and then results of a series of tests on model piles were shown to demonstrate the capability of this method in recovering the profiles of defective piles. From the available results the ability of this method to evaluate the integrity of individual pile seems very promising.

Based on the results of this study, the following conclusions can be made:
1. The traditional Sonic Echo and the Impulse Response pile integrity testing methods can only detect the location of single defect inside the model piles. Furthermore, interpretation of signal from these two tests requires some experience.

2. The Impulse Response method not only can detect the location of defects but also show the magnitude of defects inside the model piles.

3. Interpretation of signals using the IL method is more straightforward and requires less experience, especially for piles with multiple defects.

It is thus concluded that the Impedance Log method is a tool with high potential for evaluating the integrity of piles.

Acknowledgement

The work presented in this paper is sponsored by the National Science Council of Taiwan under Grant No. NSC-92-2211-E324-011 and NSC-93-2211-E324-002. The authors wish to thank the NSC for its continuing support for research in the area of nondestructive testing on the integrity of piles.

References


