Research on effect of ages and strength of concrete on wave speed in grouting pile integrality detection by low strain method in hydraulic engineering

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Abstract: Low strain method is the most common way to detect the integrality of piles in the hydraulic engineering since it has the advantages of simple operation and low condition for on-site test. In the detection of the integrality of concrete grouting pile via low strain method, wave speed is an important parameter to judge the integrity and length of pile. This paper studies the wave speed of cast-in-place concrete precast pile which is adapted in the engineering. Besides this, the relationship between concrete intensity and the wave speed of the body of precast pile at different ages is obtained. Via further verification, it is found that the relationship could be applied in the engineering piles, which renders a reference for wave speed at different ages in the integrity test of piles in the hydraulic engineering.

1. Introduction
Pile foundation, as one of the oldest base forms, was employed in the ancient time [1]. Cast-in-place pile has been widely used in the hydraulic engineering [3] since it has some edges, such as little noise pollution of construction technology [2], high bearing capacity of single pile, high degree of industrialism and mature construction technology. As reinforced concrete material appears, there are concrete piles, which has two types: the precast concrete pile and grouting concrete pile. The cast-in-place concrete pile is the most commonly used and it is a kind of pile made by in-place perforated cast-in-place concrete. Moreover, due to little vibration and less soil squeezing effect, this concrete pile is suitable for being adapted in the areas with complex site conditions, such as city with densely buildings, rivers and lakes. With the rapid development of engineering technology, the construction process of grouting pile is improved, thus expanding its application condition and scope. To meet the energy demand of society production and life in China, the relevant departments have enhanced the construction of hydraulic engineering, thus achieving rational application of water resource as well as hydroelectric resource and large-scope construction of hydraulic engineering.

Located under the ground, the quality of the body of grouting concrete pile is not obvious so that the quality control needs to strengthen during the process of construction [5]. At the same time, the quality of pile body needs to be tested via some methods after the construction. Measuring techniques of pile foundation is a relatively new industry, which is divided into bearing capacity test and pile integrity test [1]. The commonly used methods of bearing capacity test includes static test and high strain method. However, due to the large cost and the impact of the construction period, bearing capacity test could not be adapted in a larger scale in the engineering. The inspection of pile integrity
has two commonly used methods, including low strain method and cross-hole sonic logging. The low strain method is commonly used in inspecting the integrity of pile body because of its simple operation, low requirement of on-the-spot detection conditions, as well as convenient and quick operation [7].

In the integrate detection of pile by low strain method, wave speed is a significant parameter and the wave speed of pile body is concerned with the strength of the concrete, the ages of pile body, the skeletal material, the quality of treated pile head and other factors. The strength of concrete is closely related with the ages of the pile body. Therefore, the strength of concrete becomes an important parameter for the wave speed of the pile body. This paper studied the wave speed of the body of the precast grouting concrete pile and obtained the relationship between strength and wave speed of pile body at different ages. Moreover, the paper verified the grouting piles at different ages in the engineering, which provides a reference for wave speed of the integrity detection of piles in other hydraulic engineering.

2. Basic principle and experimental equipment

2.1 Basic principle

In low strain method, the commonly used method is reflection wave method, whose basic thought is that the elastic wave will transmit downward the pile body after the vertical excitation in the head of the pile. The reflection phenomenon will occur when the pile body is defective or it transmits to the bottom of the pile. By processing and analyzing the received waveform, the integrity of the pile could be recognized. Combined with the experience, both the integrity of the pile and approximate defective place via using transmitting velocity of wave and the variation of phase.

Reflection wave method has two analyzing methods, including time-domain analysis and frequency domain analysis. The main idea of time-domain analysis is as follows: selecting a section of the pile as an analytical element, and defining its density as \( \rho \) (kg/m\(^3\)), the propagation velocity of longitudinal wave in concrete pile as \( c \) (m/s), the crosssection area of the pile as \( A \) (m\(^2\)). Therefore, the result that generalized wave impedance \( Z = \rho c A \) is obtained. When the size of the pile or the material property has any change, the values of \( \rho \), \( c \), and \( A \) will change and the changing area is called wave impedance interface [1]. The ratio of wave impedance \( n \) could be expressed as following formula.

\[
N = \frac{Z_1}{Z_2} = \frac{\rho_1 c_1 A_1}{\rho_2 c_2 A_2}
\]  

(1)

When the impedance of the pile changes, the reflection and transmission waves are generated, and reflection coefficient \( F \) and transmission coefficient \( T \) could be expressed as formula (2) and formula (3) respectively.

\[
F = \frac{1-n}{1+n}
\]  

(2)

\[
T = \frac{2}{1+n}
\]  

(3)

When the wave impedance is approximately invariant, that is, \( Z_1 \approx Z_2 \), the pile belongs to integrity pile (shown in Figure 1(a)); when \( Z_1 > Z_2 \) (such as segregation, shrink diameter), \( n > 1 \), the result \( F < 0 \) and \( T > 0 \) could be obtained so that the reflection wave has the same direction as the incident wave (shown in Figure 1 (b); when \( Z_1 < Z_2 \) (such as hole enlargement), \( n < 1 \), the result that \( F > 0 \) and \( T > 0 \) is obtained so that the direction of reflection wave is opposite to the incident wave.
The main idea of frequency-domain analysis and diagnosis method is that via solving the wave equation, the difference between two adjacent natural frequencies is equal, when the pile body is integral, which could be expressed as formula (4).

$$\nabla f_n = f_n - f_{n-1} = c / (2L)$$

(4)

When the pile body exists defects, the defect frequency resonance peak $f_n'$ occurs and the frequency difference of two adjacent resonant hump could be calculated via formula (5).

$$\nabla f_n' = f_n' - f_{n-1}' = c / (2L')$$

(5)

Where $L$ represents the distance between the defective area and the head of pile. In the actual analysis, the wave speed could be calculated via formula (4) or the length of the pile could be obtained by the known wave speed. The defect area could be calculated by formula (5).

These two kinds of methods supplement each other. However, due to many external factors affecting the signal frequency in the actual detection and analysis, the frequency domain analysis is more difficult than the time-domain. Therefore, time-domain is widely applied in the actual practice.

2.2 Equipment of experiment

The dynamic testing instrument of pile RS1616K (S) (shown in Figure 2) produced by Wuhan Yanhai Engineering Technology CO. Ltd, and velocity transducer (Figure 3) were used in this experiment. The coupling agent was butero and the hammer was employed as actuator since the body of precast pile was short, the quality of the body of precast pile was easy to be guaranteed and the obtained signal was enriched.

3. In-site test

To simulate the actual engineering piles and the influence of actual condition as soon as possible, a 600mmX600mm square was used in the in-site test, the length of which was 10m (shown in Figure 4). The concrete blocks and piles were prepared at the same time and maintained under the same conditions (shown in Figure 5). The design strength grade of concrete blocks was C30. The compression tests of three groups (nine concrete blocks) and the measurement of the wave velocity of pile body were carried out via low strain method, the ages of which were 3 days, 7 days, 14 days, 28 days, 42 days and 72 days respectively.
4. **Analysis of experiment**

4.1 **Relationship between ages and intensity**

The compression tests were carried out, the ages of concrete blocks were 3 days, 7 days, 14 days, 28 days, 42 days and 72 days respectively. The results of the samples are shown in Table 1 and the relationship between ages and intensity is shown in Figure 6.

![Fig. 4 the precast pile](image1)

![Fig. 5 concrete test block](image2)

![Fig. 6 the relationship between strength and age of concrete](image3)

**Table 1 Results of compression tests of concrete blocks**

| Ages(d) (MPa) | Strength (MPa) |
|---------------|----------------|
| 3             | 16.7           |
| 7             | 24.6           |
| 14            | 30.6           |
| 28            | 34.0           |
| 42            | 37.6           |
| 72            | 39.2           |
| minimum       | 11.9           |
| maximum       | 19.7           |

From Table 1 and Figure 6, it is found that in the short ages, the strength of concrete increases rapidly with the increasing of the ages. When concrete reaches a certain strength, it will demonstrate a
gentle trend, which would not rise as the ages increase. This is because the cementation within all concrete materials is completed gradually with the increase of ages, causing the stability of the strength.

4.2 Relationship between ages and wave speed

Five precast piles whose ages are 3 days, 7 days, 14 days, 28 days, 42 days and 72 days respectively are selected to measure the velocity via strain method. The results of the samples are shown in Table 2 and the relationship between ages and wave speed is shown in Figure 7.

| Ages | Number | Wave speed (km/s) |
|------|--------|------------------|
|      | 1      | 3.30 3.55 3.83 3.92 3.93 3.97 |
|      | 2      | 3.27 3.57 3.76 3.89 3.96 3.93 |
|      | 3      | 3.26 3.52 3.77 3.91 3.94 3.99 |
|      | 4      | 3.27 3.53 3.76 3.85 3.98 3.96 |
|      | 5      | 3.31 3.61 3.76 3.86 3.92 3.94 |
|      | average | 3.28 3.56 3.78 3.89 3.95 3.96 |

From Table 2 and Figure 7, in the short ages, the wave speed of pile body increases rapidly with the increasing of the ages. When the wave speed reaches a certain degree, it stays in a stable value and it would not increase with the rising of ages. Because the strength of concrete is stable as the increasing of ages and the strength has a certain relationship with wave speed, the wave speed shows a stability when reaching a certain degree.

4.3 Relationship between the strength and wave speed

From Table 1 and Table 2, the relationship between the strength of concrete and the wave speed of the pile is obtained (shown in Figure 8).
blocks and the wave speed of pile. However, when the strength of concrete reaches a certain value, the
wave speed of the pile body hardly increases because the design grade of concrete strength is
determined and the fluctuation range is small when the strength reaches the maximum.

The result that \( y = -6E-05x^3 + 0.004x^2 - 0.075x + 3.540 \) is obtained by fitting the relationship
between strength and wave speed. The correlation index of fitting \( R^2 \) equals to 0.999, which proves
that the fitting quality is great.

5. Engineering verification

The engineering piles applying the same concrete use low strain method to measure their wave speed.
Totally 1000 piles are divided according to their ages: less or equal to 10 days, 10-20 days, 20-28 days,
28-60 days, 60-120 days or larger and equal to 120 days. The statistical results are as shown in Table
3.

| Ages (days) | ≤10 | 10~20 | 20~28 | 28~60 | 60~120 | ≥120 |
|------------|-----|-------|-------|-------|-------|------|
| Number (pile) | 85  | 72    | 201   | 188   | 139   | 315  |
| Wave speed (km/s) | 3.59 | 3.82  | 3.85  | 3.91  | 3.93  | 3.95 |

From Table 3, it is known that the conclusion in the detection of actual engineering piles is nearly
the same as the conclusion in the section 3.2, that is, in the short ages, the wave speed of pile increases
quickly. Moreover, the wave speed becomes a stable value and it does not increase with the increasing
of ages when wave speed reaches a certain degree.

6. Conclusions

(1) In the short-age period, the strength of the concrete increases as the ages increase and it tends to
rise slowly without increasing when the concrete reaches a certain strength.

(2) In the short ages, the wave speed of the pile rises with the increasing of ages and it stays at a
stable value with on increasing when the wave speed reaches a certain value.

(3) There is a positive correlation between the strength of concrete blocks and the wave speed of
the pile. The conclusion that \( y = -6E-05x^3 + 0.004x^2 - 0.075x + 3.540 \) is acquired by fitting the
relationship between strength of concrete and wave speed.

(4) The experimental results are verified by low strain method for engineering piles.

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