Low Strain Detection and Numerical Simulation of Pile Integrity

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Abstract: The low strain reflected wave method is used to detect the integrity of pile foundation of a domestic bridge, and various types of defective pile models are constructed. A large number of tests are carried out to analyze the complete pile installation and different defects. At the same time, considering the influence of pile material properties, soil parameters around the pile, boundary conditions and damping coefficient on the reflected wave, the test results are compared with the numerical simulation results. The results show that: low strain detection technology is convenient and easy to operate, but due to its own limitations, it should be combined with numerical simulation and other methods to learn from each other, comprehensive analysis, in order to better judge the integrity of the pile.

1. Introduction

Pile foundation is one of the foundation forms often used in bridge engineering and high-rise buildings. As the supporting structure of the superstructure, it is very important for the safety and stability of the structure. When the construction of cast-in-place concrete pile is carried out, because of the construction personnel's own reasons or improper construction and other factors, the pile may be broken, separated, necked, necked and other defects. If the quality of foundation piles can not be accurately detected, the quality of buildings will be affected, and even major quality and safety problems will be caused. For this reason, many scholars at home and abroad have analyzed the pile detection methods. In 1960, the method system of the model (simplifying the hammer pile soil system to mass block, spring and damper model) in the literature [1] published by Smith has been used up to now. In 1992, Fukuhara used the three-dimensional finite element method to study the low strain method to detect the integrity of pile foundation [2]. In order to make the low strain method more accurate, many domestic scholars have studied it. Wang Xuefeng [3] analyzed the integrity of pile foundation from the aspects of vibration source characteristics and soil resistance around the pile, and Chen Fan [4] studied the influence of size effect and other factors on the integrity of pile foundation.

In this paper, the low strain detection method is used to determine the integrity of pile foundation and determine the location of defects in different material properties, soil parameters, boundary conditions and damping coefficient of pile. It has important social and economic significance to improve the reliability of low strain test results and ensure the quality of pile construction.

2. The principle of Pile foundation detection

The reflection wave method is a method based on the theory of the propagation of stress wave in solid medium. The basic principle of pile measurement is: stress wave is generated by applying excitation signal on the pile top. During the process of downward propagation along the pile body, if the wave impedance interface formed by the defect of pile bottom and pile body is encountered, the reflection and transmission of sound wave will be generated, as shown in figure 1. According to the wave theory,
when the stress wave encounters the necking, segregation, honeycomb, broken pile and secondary pouring surface, the reflection wave is in the same phase as the initial dynamic phase of the incident wave because of the decrease of the wave impedance; when the stress wave encounters the neck expansion and bottom expansion, the wave impedance becomes larger and the initial phase position of the reflected wave and the incident wave is reversed. Combined with the amplitude, frequency, wave velocity of pile body and arrival time of reflection wave, the integrity, defect degree and position of pile can be comprehensively judged.

![Figure 1 Schematic diagram of pile measurement by reflected wave method](image1)

![Figure 2 Typical low strain time history curve of defective pile](image2)

During the detection, the wave velocity is calculated according to the following formula

\[ c = \frac{2L}{\Delta T} \]  

(1)

The wave velocity \( c \) of concrete is an important judgment basis. The defect location can be determined by the following formula:

\[ X = \frac{1}{2} \Delta t_x C \]  

(2)

\( L \)—distance between pile defect and sensor installation point (m);

\( \Delta t_x \) —Time difference between the first peak of velocity wave and the reflected peak of defect (s);

\( C \) —wave velocity of tested pile body (m/s);

\( X \) —distance from pile defect location to sensor installation point (m)

3. Numerical Simulation Analysis of Complete Pile

3.1 Complete Pile Model

The foundation pile is cast-in-place bored pile with a diameter of 1.2m, a length of 16.6m and a sediment of 0.05m. The pile body is made of C30 concrete, the diameter of the soil around the pile is 12m, the thickness of the soil under the pile (completely weathered granite) is 2m, the thickness of the soil around the pile (including the thickness of clay is 14.6m, the thickness of completely weathered granite is 2m), and the total thickness of soil is 18.6m. The exciting force pulse action time is 1ms, the calculation time is 25.6ms, and the sinusoidal pressure acts on the designated area of pile top when the peak value of hammering is 5000kN / m². Linear elastic materials are used for pile and surrounding soil. The relationship between pile and soil is considered to be completely continuous.

Boundary conditions: the soil around the pile is fixed in X and Y directions (U1 = U2 = 0); the pile bottom is fixed in X, y and Z directions (U1 = U2 = U3 = 0). The material parameters of pile forming soil are shown in table 1, and the structural finite element model is shown in figure 3.
### Table 1 Soil pile material parameters

| Material Science name       | Density (kg/m³) | Elastic modulus (Pa) | Poisson’s ratio | Damping coefficient |
|-----------------------------|-----------------|----------------------|-----------------|---------------------|
| pile (C30 concrete)         | 2400            | $3.0 \times 10^{10}$ | 0.2             | Alpha:60 Beta:0.0015 |
| clay                        | 1600            | $1.6 \times 10^{7}$  | 0.35            | 0.65                |
| Completely weathered granite| 2500            | $3.5 \times 10^{10}$ | 0.18            | 0                   |
| Pile bottom sediment        | 2000            | $2.3 \times 10^{10}$ | 0.18            | 0                   |
| sand                        | 1800            | $4.0 \times 10^{7}$  | 0.25            | 0.15                |
| Segregation (C15 concrete)  | 2250            | $2.2 \times 10^{10}$ | 0.23            | 0                   |

3.2 Comparative Analysis of Numerical Simulation And Actual Measurement of Complete Pile

The Miss stress nephogram and velocity time history curve of the complete pile are shown in figure 4 to figure 7.

It can be seen from Figure 7 that the length of pile body is 16.60m, and the propagation velocity of reflected wave is 3565m/s. read the data from figure 7, the time of the first peak value of velocity wave and the first peak value of pile bottom reflection are $5.64 \times 10^{-4}$ seconds and $1.01 \times 10^{-2}$ seconds respectively. By substituting these data into formula (1), the calculated pile bottom position is $L = 17.00m$, which is close to the pre-defined pile bottom position of 16.60m.

4 Finite element numerical simulation analysis of defective pile.
Figure 7 Velocity time history curve of Complete pile

**4. Finite Element Numerical Simulation Analysis of Defective Pile**

In the field pile detection, the defect type is easy to identify, but the defect location is often not accurate. For the common defective pile, the finite element model is established by ABAQUS and the numerical simulation is carried out. The curve obtained is analyzed comprehensively with the reflected wave curve detected by experiment, and the defect type and location are judged. The length, boundary conditions and pile-soil material parameters of the following defective piles are consistent with the complete pile model.

**4.1 Necking Pile Model**

When in the construction site, the pipe pulling speed of the cast-in-place pile is too fast and the height is low, resulting in insufficient extrusion force and necking [7]. Necking size has a great influence on defect judgment. When the necking size is small, the natural frequency of the pile body and the forward reflection wave at the necking will be superimposed, which will affect the accuracy of the necking position; when the necking size is large, the defect position can be calculated more accurately. The necking position is shown in figure 8, and the time history curve of simulated necking velocity is shown.

![Figure 8 Diameter of necking site 300mm](image)

It can be seen from figure 8 that the length of pile body is 2.10m and the propagation velocity of reflected wave is 3870m / s. Read the data from the numerical simulation results to get the time dependence of the first peak value and the first reflection peak value of the velocity wave is $24 \times 10^{-4}$ seconds and $5.64 \times 10^{-4}$ seconds respectively. The second peak time of necking reflex is $8.99 \times 10^{-4}$ seconds. By substituting the data into formula (2), the necking position is calculated as $x = 1.500$m, which is close to the pre-defined necking position of 0.70m-1.40m.

**4.2 Model of Belled Pile**

In this experiment, the expanding neck appears at 0.7m of the pile body, the relative necking appears at 1.4m, and the normal phase reflection appears at 1.4m of the pile body, which is due to the relative expanding neck. In this experiment, although the pile body is too short, it is easy to appear waveform superposition, which affects the accurate judgment of waveform and defect location, but the reflection of pile bottom can still be seen. The wave propagation in the pile is affected by the neck expansion defect. When the neck expansion defect is not obvious, the wave velocity is similar to that of the intact pile. The expanding part and the time history curve of simulated expanding speed is shown in figure 9.
It can be seen from figure 9 that the length of pile body is 2.10m, and the propagation velocity of reflected wave is 3650m/s. Read the data from Figure 9, the time of the first peak value of velocity wave and the first reflection peak value of expanding neck are $1.24 \times 10^{-4}$ seconds and $5.64 \times 10^{-4}$ seconds respectively, and the time of the second peak value is $8.99 \times 10^{-4}$ seconds. By substituting the obtained data into formula (2), it is calculated that the neck expansion position is $x = 0.803m$, $X' = 1.414m$, which is close to the pre-defined neck expansion position of 0.70m-1.40m.

4.3 Broken Pile Model
The length, boundary conditions and material parameters of the pile are the same as those of the complete pile model. The position of broken pile and the time history curve of simulated broken pile speed is shown in figure 10.

It can be seen from figure 10 that the wave velocity is 3860m/s and the pile length is 2.10m. The wave crest of defect reflection wave can be observed at 0.7m of pile body. When the defect is a single broken pile, the defect is easy to judge, and the reflection at the bottom of the pile can not be seen.

Reading the data from the numerical simulation results in figure 10 the time of the first peak value of velocity wave (i.e. excitation pulse peak value) and the first peak value of fracture reflection is $1.24 \times 10^{-4}$s and $4.45 \times 10^{-4}$s respectively. By these data into formula (2), the calculated fracture location is 0.62m, which is close to the pre-defined fault location of 0.70m.

4.4 Segregation Pile Model
The segregation of the pile and the reduction of the concrete strength of the pile body are mainly due to the improper concrete mix proportion or poor concrete grading, poor vibration and not strictly implementing the mix proportion; the concrete falling from a high place may also cause segregation; the material of the pile body is unqualified, such as the high content of sand and stone, the unqualified cement quality, etc. See Figure 11 for the segregation position and the time history curve of simulated segregation velocity.
According to figure 11, the length of the pile body is 2.10m, and the wave velocity is 3860m/s. Although the position, wave velocity and pile length of the reflected wave at the bottom of the pile in the segregation layer are different from those of the normal pile, it is difficult to judge the segregation thickness only in the time history curve, which needs to be analyzed in combination with the frequency domain diagram.

Reading the data from figure 11, the time of the first peak of velocity wave and the first peak of segregation reflection are $2.12 \times 10^{-4}$ seconds and $8.99 \times 10^{-4}$ seconds respectively. By substituting the obtained data into formula (2), $x = 1.34 \text{m}$ is calculated, which is close to the pre-defined 1.40m.

5. Epilogue

In this paper, considering the influence of soil around the pile on the reflected wave, the field test results and numerical simulation of pile foundation are compared:

(1) Considering the influence of the soil around the pile, more material properties are needed, such as the plasticity and viscosity of the soil.

(2) In this study, field detection combined with numerical simulation is analyzed, only the defect location is studied, and the defect degree is not studied, which needs to be improved and improved.

(3) Comprehensive consideration of field testing and numerical simulation, but also need to improve constantly, can be used to carry out quantitative analysis, reduce variables, a common factor affecting the test results factor analysis.

(4) Because the selection of damping coefficient has certain experience, it may also be an influencing factor. Through this study, it is found that if the pile body is short, it will greatly affect the waveform curve, increasing the difficulty of judgment. Therefore, the selection of damping coefficient according to different conditions is also a direction worthy of further study.

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