Application Research of Pipe Pile Detection Technology based on Impact Elastic Wave

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Abstract. The practical application of the low strain method in the detection of prestressed pipe piles is not ideal. After investigation, there is a practical and feasible method, namely the impact elastic wave method, which can be used for nondestructive testing of prestressed pipe piles. This paper proposes a nondestructive testing technology for prestressed pipe piles, the impact elastic wave method, and introduces a signal pickup device for prestressed pipe piles with side walls and bottom damping, improving the technical bottleneck of low strain method for detecting hollow thin-walled structures such as pipe piles, and solving the problems of detecting the length and integrity of hollow thin-walled prefabricated pipe piles. Through large-scale field measurement and on-site pile excavation inspection of all known pipe piles, it has been shown that this detection method can more effectively detect pipe piles. Through measurement and inspection of all known pipe piles, a standard inspection process for the length and integrity of all pipe piles can be established and effectively applied to the inspection of actual projects; Through field inspection, the accuracy of the testing method for pipe pile measurement has been confirmed, and a fast, effective and reliable method for pipe pile measurement has been proposed.

Keywords: prestressed pipe pile; shock elastic wave method; pile length and integrity test.

1. Introduction

The technology of prestressed concrete pipe pile can be divided into post-tensioning method and pre-tensioning method to construct the prestressed concrete pipe pile together[1-2]. The pre-tensioned pipe pile by pretension method refers to a new prefabrication system of thin hollow tubular steel bars made by centrifugal forming and molding method with pretension prestressing technology[3-5]. The main structural member of the prestressed pipe pile is composed of cylindrical pile, coil formwork and thin steel sleeve. At present, pipe piles are generally divided into two strength levels: prestressed concrete pipe piles and prestressed high-strength concrete pipe piles, according to concrete strength grade or effective stacking precompression stress division. Prestressed pipe pile has higher strength level and impact resistance, and the vertical load-bearing force of single pile foundation is larger. It has the characteristics of good soil penetration and almost no pollution to the surrounding environment, saving the excavation time and the excavation cost. Due to a series of advantages of prestressed pipe pile, it has been widely used in different places in China, especially in soft soil area in coastal areas[6-8]. However, problems such as insufficient bearing capacity and serious damage to the length and integrity of pile foundation appear in the specific site construction process, such as: production, hoisting, transportation operation is not standard[9-10]. When piling, quality control measures are not in place, resulting in less leakage play phenomenon often occurs because the quality monitoring of piling is not enough, resulting in low strength bearing capacity of pipe pile, such as pile has not reached the engineering design height, floating, tipping, deflection, pile rupture, pile top broken etc., because of the above problems, often lead to engineering quality accidents[11-13].

At present, in the national standard "Technical Regulations for Testing Highway Engineering Foundation Piles" (JTG/T3512-2020)8.1.1, the low strain method is suitable for inspecting the integrity of concrete structural piles and the location and degree of defects. In practical engineering applications, the pile top excitation signal is constrained by the inner wall and outer wall of the pipe pile, and the interference to the signal is complex. In practical engineering applications, due to the excitation signal of the pile top is constrained by the inner wall and the outer wall of the pipe pile, which has complex signal interference, and it is difficult to identify the integrity of the pile body and the pile Bottom position, so the detection accuracy is difficult to guarantee. Through research, it is clearly pointed out that PIT test method (low strain) is not suitable for hollow pile/column test in the United States federal standard Specification ASTM-D-5882-00, so it is difficult to effectively detect the quality of pipe pile by using low strain technology.

In order to improve the technical difficulties of traditional methods such as acoustic transmission method, magnetic measurement method and side hole transmission method in pipe pile detection. By studying the characteristics of hollow members of pipe piles and making use of the signal propagation theory of impulse elastic wave in pipe piles, the academic circle has made an in-depth study of the existing signal picking device and analysis of the reflected signal of pile, and proposed a detection method based on impulse elastic wave: The key technique of this method: (1) Signal extraction device based on side wall and bottom damping. Damping has an obvious inhibitory effect on vibration signals. As for the receiving signals, a special device is designed at the receiving end of the sensor to suppress the high-frequency signals generated by knocking at the top of the pile, so as to effectively extract the signals of the pile and the pile bottom. (2) Propose an improved signal filtering method. The above devices and methods fully combine the structural characteristics of pipe piles, reduce the influence of pipe pile joint signals, realize effective extraction of pipe pile defects and bottom reflected signals, break through the technical bottleneck that low strain detection technology is not suitable for detecting hollow thin-wall structures, and realize the detection of pile integrity and length of prestressed pipe piles.

2. Study on elastic wave propagation mechanism of pipe pile

In the sinking process of the pipe pile, the surrounding concrete body will produce different degrees of soil squeezing, and the phenomenon of soil expansion around the pile and de-welding dislocation at the technological position of the pile may occur when the situation is more serious. The propagation of the impact elastic wave signal inside the pipe pile will be changeable and uncertain. So it is necessary to deeply study the influence mechanism and law of elastic wave on the structure of pipe pile.

3. Detection method and principle

The main test method of pipe pile is impact elasticity wave method (Figure 1). The advantages of this method include: large excitation energy, long band (correspondingly small decay), good stability of basic parameters (wave velocity), etc., resulting in a deeper detection depth. It is applicable not only to newly laid pipe piles, but also to those laid pipe piles with a long buried duration. When the elastic signal caused by excitation is transmitted, the mechanical wave impedance (generally used to represent the mechanical resistance of the material, here refers to the cross section area) will change to some extent when the elastic wave signal appears in the different material changing parts of the scattering section (such as the pile bottom, broken pile or severe segregation, etc.) or the pile cross-sectional area changing (such as reducing or expanding diameter). The transmitted elastic signal causes the reflection and transmission of the wave at the interface of the section where the resistance changes.

During detection, two special sensors are placed on the top of the prefabricated pipe pile, and frequency conversion vibration excitation is adopted to stimulate the pile top. The elastic wave signal of excitation is transmitted down the pipe pile. When the signal meets the interface of impedance difference, the signal will be reflected in different degrees. Combined with the propagation velocity of elastic wave in the precast pile, the pile length and the position of pile body defects can be determined(Figure 2).

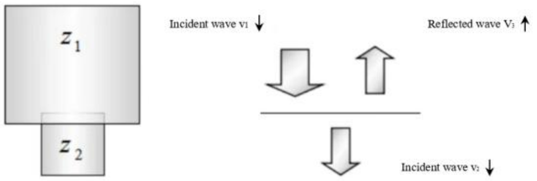
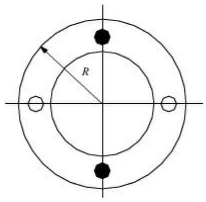


Fig. 1. Signal propagation diagram of impact elastic wave in pipe pile



●：Hammer the shock point ○：Sensor mounting point

Fig. 2. Schematic diagram of excitation and signal receiving point installation

3.1 Basis of preliminary work

3.1.1 Main difficulties

As mentioned above, the principle of pipe pile length and integrity testing (using impact elastic wave reflection) is relatively simple, and the principle of PIT (integrity of solid concrete foundation pile) is basically the same. However, since the 1980s, PIT testing technology has been applied in the actual testing of solid concrete pile, and has achieved a very mature technical development, but it is not until recently to break through the technical bottleneck of nondestructive testing methods for the length and integrity of pipe pile. The reason for the difficulty is that the section shape and material of pipe piles are complex and special, and the pipe pile pass length is not a whole. Such piles are connected through segment joints and driven into construction, etc. The differences between test and test objects are shown in Table 1 and Figure 3.

Table 1 Differences between test objects

Test object	Foundation pile	Pipe pile
Section characteristics	The section is solid and dense	Thin wall hollow section
Number of joints	No more than 2	No more than 4

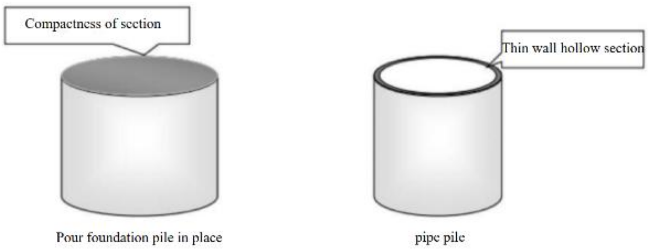


Fig. 3. Difference between test subjects

Through comparison, it is found that there are two main differences between the test objects, one is the shape, the other is the number of joints, both of which will have a great impact on the detection information in the transmission process of pipe pile using elastic wave propagation. Therefore, compared with the traditional solid concrete foundation pile construction detection, the technical difficulty of pipe pile test is greatly improved. So it is very important to study the propagation mechanism of test signal in pipe pile.

(1) Excitation signal attenuation

The waveform information generated by the excitation force attenuates rapidly when the section of concrete base pile structure is poured in dense (Fig. 4 a), while the excitation signal attenuates slowly in the hollow thin-walled cylindrical structure such as pipe pile (Fig. 4 b). There are two reasons for this. One is that the vibration signal remains for a long time, and the other is that the sound signal generated by the strike will resonate with the chaotic signal in the middle cavity. Moreover, the signal components will become more complex and there will be fewer available signals.

(a) solid concrete pile (b) pipe pile

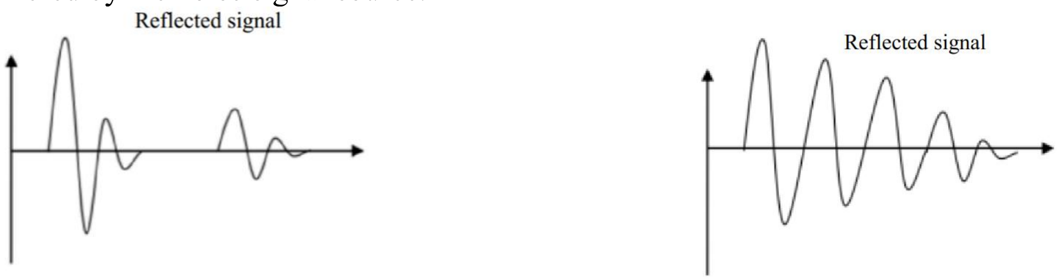
Fig. 4 Attenuation of excitation signal

(2) Recognition of reflected signals

For the following reasons, it is very difficult to identify and extract the reflected signal from the bottom of pipe pile:

1) Signal attenuation rate in pipe pile transmission is slow. Because the capacity generated by the exciting force is mainly dispersed into the concrete through the contact between the pipe pile and the surrounding concrete body, the larger the range of pile ratio table, the slower the attenuation rate of the capacity. Therefore, the specific table size of the solid component can directly determine the size of energy escape. Therefore, the pipe pile is a thin-walled hollow system, and its specific surface area is much larger than that of ordinary solid concrete pile.

2) The excitation signal in ideal state and the state interfered by noise signal source are shown in Fig. 5. The former is easy to recognize the reflected signal; The latter in the excitation signal has not fully converged before the reflected signal has arrived, when the residual vibration time long condition appears, it is very difficult to accurately identify and extract the effective reflected signal interfered by the noise signal source.



(a) Ideal state (b) Noise interference state

Fig. 5 Pulse excitation signal

Although the PIT (low strain) detection technique has been quite perfect in the construction detection of solid concrete foundation pile more than 20 years ago, effective and feasible testing techniques have not been developed for the detection of pipe pile structure until recently.

3.1.2 Key Technologies

Through in-depth research, we have successfully developed a series of relevant technologies to further improve people's ability to identify and extract reflective information at the bottom of pipe piles and the accuracy of analysis, such as the suppression of residual vibration signals, the fixation of sensors, the improvement of signal-to-noise ratio, intelligent analysis function and other measures. In the detection equipment implantation, the detected information was analyzed by the precise spectrum analysis technology FFT and MEM, and the information was processed by the information Matching analysis method to realize the reflection information extraction.

Through the practice of reflected signal extraction technology, we also study the intelligent analysis method mechanism to improve the signal-to-noise ratio (S/N) and measurement accuracy. The intelligent analysis method mechanism includes the following functions: (1) Mathematical statistics are adopted to obtain the best measurement results through comprehensive calculation in multiple measurement data;(2) Adopt the most suitable analytical means according to the different length intervals of pipe piles; (3) Add a variety of checking functions in the analysis process, can effectively prevent obvious errors in the process of program analysis. When the dispersion of test information is large, alarm information can be automatically generated, and at the same time of testing, it can also evaluate the dispersion of various information, providing an objective and correct evaluation basis for the accuracy of the field information. The reflection information extraction technology is adopted, and spectrum analysis skills (FFT, MEM) are implanted in the instrument to analyze the measured information and the information Match（MatchiNg） your analytical skills to manage information.

3.2 Research Progress

Through preliminary expert investigation and laboratory test, preliminary results have been obtained for the key technologies of the pile length and integrity detection of prefabricated pipe piles, which provides a technical path for the optimization research of pipe pile detection methods.

(1) Research on length detection technology and equipment of hollow thin-wall structure (deep impact elastic wave detector of steel guardrail column).

For steel guardrail column (wall thickness 4.5mm, outer diameter 140mm, length about 2m) using an innovative detection method - impact elastic wave buried depth detection technology, the original technology has been widely recognized at home and abroad, have applied for a national invention patent (patent name: the use of impact elastic wave measurement guardrail steel column buried depth detection equipment and detection methods. Patent number: ZL 200610003437.6). This detection method has entered the standard of transportation industry, and the technology breaks through the technical bottleneck that impact elastic wave is not suitable for testing hollow thin-wall structure, and provides a solid foundation for the following pipe pile detection technology(Figure 6).

Fig. 6. Steel guardrail column buried impact elastic wave detector

(2) Metal Section drill pipe length test (somewhere in Beijing 2020.07)

Pipe pile connecting is an operation often needed in construction. Because the length of pipe pile is not enough, it is usually necessary to connect another pipe pile on the pipe pile in construction, which is called pile connecting. Pipe pile is generally used welding method, sulfur cement anchor method and flange method three, commonly used is welding method. Poor connection of pipe pile will affect the construction quality and the stability of the building, so the pile should be constructed according to the requirements of the code, such as controlling the height of pile and keeping the upper and lower section pile straight and so on. During the construction of prefabricated pipe pile, it is generally welded or splicing with 1 ~ 4 sections of prefabricated pile. In the detection of low strain method, the signal is affected by the gap at the weld or joint. After the excitation of the pile top, most of the signal energy is reflected in the gap, and only a small part is propagated down. The sensor installed on the pile top can not collect the effective pile bottom reflection signal, so it cannot analyze and determine the pile length and pile body defects.

It is precisely because of the existence of the length and segment of the pipe pile that the reflected signals at the interface of the impedance difference between each precast segment pile will interfere with the reflected signals of the pile bottom and pile body, which will bring great difficulty to the detection of the pipe pile. The traditional low strain detection method has been unable to effectively distinguish the reflected signals at the segment, defect and pile bottom.

In view of this situation, we conducted a large number of field tests, data analysis and technical research according to the theoretical basis of the impact elastic wave propagation in the pile, fully combined with the structural characteristics of the pipe pile, reduced the impact of the signal at the joint of the pipe pile, realized the effective extraction of the pile defects and reflected signals at the bottom of the pipe pile, and developed corresponding technologies and invention patents to break through these problems. Finally, under our unremitting efforts, this detection technology has achieved phased results.

1) Boundary condition requirements

According to the elastic wave characteristics of impact, most pipe piles can be regarded as one-dimensional bar. The boundary conditions satisfying the one-dimensional bar are:

$$\left.\begin{array}{l}\lambda > 2D \\ D < \dfrac{1}{5}L\end{array}\right\} \tag{1}$$

Where λ is wavelength; D is diameter of pile; L is pile length.
General foundation pile can meet such conditions.

2) Propagation theory of impact elastic waves along the axis of a one-dimensional bar
According to the hammering method, the elastic wave in concrete foundation pile along the vertical axis of the one-dimensional transmission law and principle are as follows：

(1) Pile body is in free state

Assume that the vertical axis of concrete foundation pile rod is the X-axis, as shown in Fig. 7 With concrete pile shaft is assumed to be uniform, pile material uniformly continuous, cross section area, elastic modulus, density, respectively, with A 、 E 、 ρ , said so, arbitrary cross section of the micro unit x , dx affected by free vibration of the longitudinal force p disturbance, vibration displacement is denoted by $u(x,t)$.

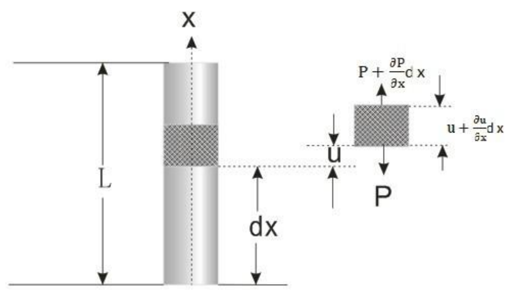


Fig. 7. Longitudinal vibration of particle in one-dimensional bar

The element dx is at $x+dx$, and $p(x)$ represents the longitudinal tension generated after disturbance.

$$p(x) = AE\varepsilon \tag{2}$$

Where $\varepsilon(x) = \dfrac{\partial u}{\partial x}$, so the above equation can be written as

$$p(x) = AE\frac{\partial u}{\partial x} \tag{3}$$

The total tension at $x+dx$ section is:

$$p+\frac{\partial p}{\partial x}dx=AE\left(\frac{\partial u}{\partial x}+\frac{\partial^2 u}{\partial x^2}dx\right) \tag{4}$$

According to Newton's law, the acceleration principle of the object generated by the balance force difference, namely:

$$\frac{\partial p}{\partial x}dx=\rho Adx\frac{\partial^2 u}{\partial t^2} \tag{5}$$

After sorting it out, there are:

$$\begin{aligned} AEdx\frac{\partial^2 u}{\partial x^2}&=\rho Adx\frac{\partial^2 u}{\partial t^2} \\ \frac{E}{\rho}\cdot\frac{\partial^2 u}{\partial x^2}&=\frac{\partial^2 u}{\partial t^2} \end{aligned} \tag{6}$$

To: $C^2=\frac{E}{\rho}$, through sorting and calculation, the differential equation of longitudinal particle vibration of pile rod in one-dimensional direction can be calculated:

$$\frac{\partial^2 u}{\partial t^2}=C^2\frac{\partial^2 u}{\partial x^2} \tag{7}$$

It can be known that C is the elastic wave of impact, and the speed of axial propagation of pile rod in the same 1D, namely:

$$C=\sqrt{\frac{E}{\rho}} \tag{8}$$

The general solution of the wave equation (7) is:

$$u(x,t)=f(x-Ct)+g(x+Ct) \tag{9}$$

Equation 9 shows that the original waveform does not change due to the initial disturbance, $x-Ct$ and $x+Ct$ represent upward and downward transmission of arbitrary function respectively, both parameters are satisfactory and propagate at the speed of C . According to the characteristics of pile detection, we generally study the downward propagation of pile top knock.

(2) The pile body is in a non-free state

When the elastic wave generated by the percussion at the top of the pile propagates down the pile, it is bound to be affected by the pile buried in the stratum and the friction between the pile and the surrounding soil, so the wave equation derived is:

$$\frac{\partial^2 u}{\partial x^2}=\frac{1}{C^2}\frac{\partial^2 u}{\partial t^2}+\frac{h}{EA}\frac{\partial u}{\partial t} \tag{10}$$

The friction damping coefficient of the stratum around the pile on the pile is represented by h, and the symbols of other parameters are consistent with the previous assumptions in this paper. According to the calculation, the propagation velocity of the elastic wave in the pile under this working condition is still C.

(3) Elastic wave velocity

In the three-dimensional body (i.e. the wavelength of the elastic wave is smaller than the structure) the wave speed of the infinite body is:

$$V_{p_3}=\sqrt{\frac{E}{\rho}\cdot\frac{(1-\mu)}{(1+\mu)(1-2\mu)}} \tag{11}$$

Generally, Poisson's ratio of pile concrete is about 0.2, can calculate the $V_{p3} = 1.05C$. This is why the P wave velocity detected by the transmission method is higher than that of the one-dimensional rod measured by the reflection method. In the following research, we get inspiration from the underground drill pipe engineering length detection, break through this technical problem, and gain valuable experience and achievements in the stage. Special testing equipment was used to detect the length of underground drill pipe in a certain project. According to the field testing results, the detection method based on shock elastic wave can effectively detect the length of segment splicing (threaded connection) drill pipe, and the signal between segments has little influence on the reflected signal of pile bottom. The signal extraction technology in this device lays the foundation for the successful research of this subject.

4. Wave velocity test of pipe pile

In order to measure the length and integrity of precast pipe pile accurately, it is necessary to calibrate the wave velocity of pipe pile accurately. According to the formula $V=\frac{2L}{T}$, it is necessary to drive the same test pipe pile of known length into the soil under the same conditions (hammer or static pressure). The wave velocity under the two driving conditions (hammer or static pressure) is calibrated by the pipe pile quality detector to determine the wave velocity for detection. For the pipe pile driven into the soil under static pressure, the wave velocity is 4.0km/s. The wave velocity of pipe pile driven into soil under the condition of hammer is 4.15km/s.

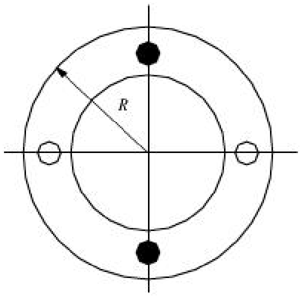
The empirical wave velocity of pipe pile driven under these two conditions should be paid attention to: not only cement, sand, stone, water, admixture and other factors that determine the concrete mix ratio of pile will affect the test wave velocity of pipe pile; Some factors in the process of construction, such as technological environment and conditions, soil quality around the pile and nearby soil, will also affect the propagation speed of the empirical wave velocity of the pipe pile driven under the two conditions. Therefore, when the test result of pile length has a large deviation, it should be determined according to the actual working condition analysis.

5. Field application and verification cases

In order to verify the feasibility and accuracy of this detection method, the length and completeness of prefabricated pipe piles for an expressway extension project were tested in Wuhu City, Anhui Province. According to relevant data, the design length of pile 1# is 33m (11+11+11), the design length of pile 2# is 11m, concrete strength of pipe pile C80, pile diameter 400mm, wall thickness 60mm. The length of each section is about 8~13m. During construction, the connections between piles are welded and assembled, and the construction methods are divided into static pressure and hammer.

The pipe pile quality detector based on the impact elastic wave method was used in this test to detect the length and integrity of the prefabricated pipe piles. The two pipe piles tested were constructed when there were side stations to determine the length of the piles.

The wave velocity of pile was calibrated by standard method in advance, and then its length and integrity were measured on site. Measuring point layout requirements: the vibration excitation and percussion points of pipe piles and the trusted points of sensors should be on the same horizontal interface as far as possible. In addition, the measuring points (percussion points and trusted points) should be connected to the pile center at 90º Angle, and the installation position should be at 1/2 of the pile wall thickness as far as possible (as shown in Fig. 8 and Fig. 9). During field detection, shovel and broom are used to remove the residual soil on the end face of pipe pile, and then two special sensors are arranged symmetrically at both ends, and hammer and force rod are used respectively to collect data, with no less than 3 valid data in each group(as shown in Fig.10 and Fig. 11).



●：Excitation point ○：sensor

Fig. 8. Installation position of excitation point and sensor

Fig. 9. Onsite detection scenario

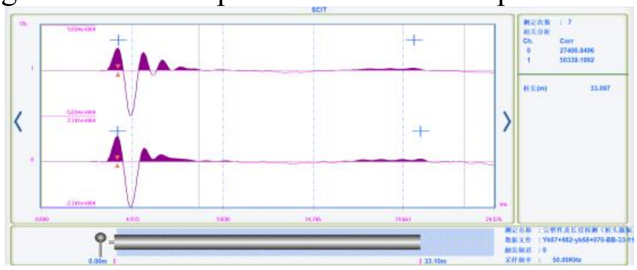


Fig. 10. Detection waveform of 1# pipe pile with normal length

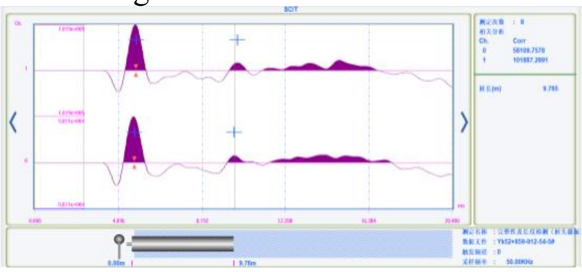


Fig. 11. Detection waveform diagram of abnormal length of 2# pipe pile

Table 2 Differences between test objects

Test object	Design pile length (m)	Measured pile length (m)
1# pipe pile	33	33.097
2# pipe pile	11	9.765

According to the test results, the length of 1# pipe pile meets the design requirements, while the length of 2# pipe pile is lower than the design requirements.

After the completion of the pipe pile detection, the pile pulling verification was carried out on site in time according to the test results. After the field detection and pile pulling verification, the test results were within the allowed range of error, the detection accuracy met the requirements of the industry and the practicability was good, which provided a very effective practical basis for the detection technology in the future.

6. Summary

The pile forming quality of pipe pile is affected by joint location and quantity, groundwater level around pile, friction coefficient of pile wall, stratum and surrounding environment, which leads to the uncertainty of shock elastic wave velocity in the process of pipe pile transfer. The empirical wave velocity is affected by the raw materials and mix ratio of pipe pile concrete, construction technology, surrounding soil and other factors, so the test results of the pipe pile length and integrity detection method based on the empirical wave velocity may be significantly different from the actual situation, so it needs to be evaluated according to the actual working conditions.

From the practical application case of length and integrity detection of a high-speed prefabricated pipe pile in Anhui province, this paper proposes that the impact elastic wave pipe pile detection technology using measured sound velocity of pipe pile can effectively reduce the test deviation caused by raw material mix ratio, construction technology and surrounding soil mass to a large extent. Successfully make up for the defects of pipe pile length and integrity in testing technology in the field of quality testing of pipe pile in nondestructive testing industry, and put forward effective testing technology.

In order to further improve the detection accuracy of this detection method, we need to rely on the relevant units and colleagues in the industry to carry out a lot of field application and verification in order to make this method serve the length and integrity detection of pipe piles with higher accuracy.

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