Reliability study on the application of reflected wave method in integrity test of pre-stressed pipe pile

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ABSTRACT. *Reflection wave method is a common approach to detect the foundation pile. However, if it is applied to the integrity test of pre-stressed pipe pile, the test results may vary with the pile-soil conditions. To evaluate the reliability on the application, this paper designs model piles with different degrees of defects, and tests the integrity of these piles at different stages. Through the analysis of the test curves, a large discrepancy was found between the pre- and post-sinking defects of the pre-stressed pile piles, indicating that the pile-soil conditions have a major impact over the defect causes and the limitations of the reflected wave method.*

RÉSUMÉ. *La méthode par ondes de réflexion est une approche courante pour détecter le pieu de fondation. Toutefois, s'il est appliqué au test d'intégrité d'un pieu de tuyau précontraint, les résultats de ce test peuvent varier en fonction des conditions de pieu-sol. Afin d'évaluer la fiabilité de l'application, des pieux modélisés avec différents degrés de défauts ont été conçus dans cet article et leur intégrité à différentes étapes a été testée. A travers les analyses des courbes de ce test, un écart important a été trouvé entre les défauts avant et après l'enfoncement des pieux de tuyau contraint, ce qui indique que les conditions de pieu-sol ont un impact majeur sur les causes des défauts et les limites de la méthode des ondes réfléchies.*

KEYWORDS: *defect detection, prestressed pipe pile, reflection survey, reliability.*

MOTS-CLÉS: *détection des défauts, pieu de tuyau précontraint, enquête de réflexion, fiabilité.*

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1. Introduction

Based on wave theory, reflection wave method has been applied into prestressed pipe pile tests for several decades (Chen *et al*., 2014). Especially during the past decade, with the extensive use of prestressed pipe pile, state and local governments have successively promulgated a series of norms such as “Prestressed Concrete Pipe Pile”, “Code for Acceptance of Construction Quality of Building Foundation”, “Pretensioned Spun Concrete Piles” and “Technical Code for Building Pile Foundations”, which have clearly defined the design and construction of prestressed pipe pile (Akagi *et al*., 1983; Guangdong Standard, 2008). Moreover, the regulatory authorities and inspection industry associations frequently conduct check experiments to verify the relevant capabilities of testing institutions (He, 2009). However, the design of model pile defects in proficiency testing cannot fully reflect the defects and actual testing conditions of engineering piles (Xu, 2009; Chow *et al*., 2003). The literature published in recent years only involve the problems existing in the theoretical analysis and detection process, but seldom contain the analysis and study on simulation of pile defects in practical engineering (Wang *et al*., 2012). In this study, both domestic and foreign low strain dynamic testing machines have been selected for the detection of the prestressed pipe pile with the artificial defects and result analysis, so as to enhance cognition of the integrity test technique of prestressed pipe piles and to reduce both false positive and false negative in actual detection projects considering construction safety.

The rest of this paper is organized as follows. Section 2 introduces the geological survey of test site. Section 3 introduces the fundamental principles and the designs of the test pile defect. Section 4 gives the pile reflection waves under different pile environments. Section 5 analyzes the results from different test groups 7 days after piling. Section 6 gives the conclusions

2. Geological survey of test site

See table 1**.**

Table 1. Geological conditions

Elevation	Soil layer	Description	Groundwater Table
0~-3m	miscellaneous fill	dark gray / grayish yellow, moist, unconsolidated ingredients: sandy clay dominated, crushed stones and construction waste supplemented	-2.75m
-3m~-17m	residual sandy sticky clay	gray, moist, easily softened in water	

-17m~-19.6m	completely decomposed granite (CDG)	grayish yellow, hard	
-19.6m~25.1m	intensely weathered granite	grayish yellow, clearly structured protolith, half rock half soil core with moderately weathered fragments	

3. Fundamental principles and test pile defect designs

The model pile defects of prestressed pipe pile contain Pile 1 with complete structure, Pile 2 with minor defects, Pile 3 with obvious defects and Pile 4 with severe defects or fractures. According to “Building Pile Testing Technology Code” (JGJ106-2014), the quality of piles can be divided into four categories based on the test results (Institute of Foundation Engineering, China Academy of Building Research, 1996):

Pile 1: The regularity of the dynamic test waveform attenuates, and the reflection from pile bottom is distinct. The pile is in good condition and reaches the designed length. The wave velocity is normal, and the concrete strength is higher than the designed grade.

Pile 2: The dynamic test waveform shows small distortion, and the reflection from pile bottom is distinct. There are small defects in the pile, such as broaching, mild gapping and local mild separation which have no effect on single pile bearing capacity.

Pile 3: The dynamic test waveform reveals obvious irregular reflection, corresponding pile defects being crack, separation, 1/3 gapping above pile section, low wave velocity and concrete below designed strength grade which have certain influence on single pile bearing capacity.

Pile 4: The dynamic test waveform is seriously distorted, which corresponds to the pile defects of fissure, severe separation, intercalated mud, severe gapping, rift, acute length insufficiency or inadequate contact with bearing strata, etc. Pile 4 is unusable for engineering applications.

The widely used foundation pile integrity test by low strain reflected wave method is theoretically based on the inner stress propagation of elastic solid in one-dimensional space (Ding *et al*., 2014; Ding *et al*., 2011). When the pile length is far much larger than the pile diameter (some data suggest a length-diameter ratio over above one order of magnitude), the pile can be recognized as a one-dimensional elastic member. Hammer (or force rod) can be utilized to impose a small impact force F(t) to the pile top, exciting a stress wave propagation through the pile. If the stress wave comes across pile section change in its propagation, the wave impedance will change as well, causing a stress wave reflection in this section. In this case, time history curves composed of initial signals and pile defects or reflections produced at the pile bottoms can be received by the sensors (accelerometer or speedometer) installed at the pile top; the collected waveforms with pile body quality information can also be processed and analyzed via low strain pile dynamic tester; and the pile integrity shall be determined in conjunction with relevant geological data and construction records. The time-domain signals received at the pile top also include the superposition information caused by the increase or decrease (wave impedance decrease) of the soil resistance at the pile side (Ding *et al*., 2009; Ding and Tan, 2011). Therefore, the pile defect position can be estimated according to that of abnormal reflection signals in time-domain curves; and likewise the defect nature of broken pile can be judged by the phase change or frequency analysis of reflected signals.

The stress wave propagation principle is shown in Figure 1.

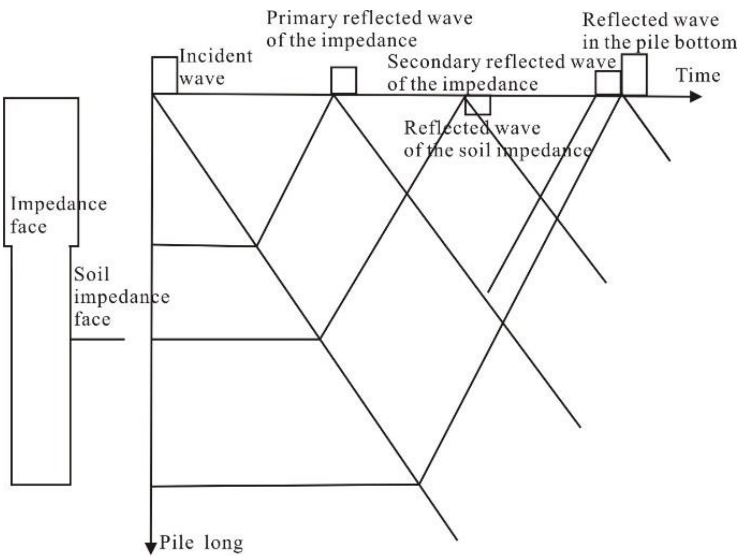

Figure 1. Schematic diagram of stress wave propagation

Mathematical theory formulas are as follows:

The propagation velocity of stress wave in concrete is:

$$C=(E/P)1/2 \quad (1)$$

Definition of pile impedance:

$$Z=EA/C=A\times(EP)1/2=ACP \quad (2)$$

C-propagation velocity of longitudinal wave in the pile of concrete, m/s;

E-elasticity modulus of concrete, N/m^2.

P-concrete density, kg/m^3.

Z-generalized wave impedance, Ns/m;

A-sectional area of pile body, m^2.

As can be seen from the above formula, impedance Z is affected by sectional area of pile body and concrete strength.

Once stress wave V enters the medium with impedance Z2 from that with impedance Z1, the reflected wave Vf and the transmitted wave Vt are generated.

$$Vf=V\times(Z1-Z2)/(Z1+Z2) \quad (3)$$

The detection waveform of foundation pile is also related to the resistance of soil around piles. It is generally believed that the reflected signals with larger mutation are mainly affected by impedance change of pile, while those with wider gradient range are greatly affected by soil resistance. The time-domain waveform of integrate pile decreases regularly with a smooth wave curve and higher wave velocity. There are one or several obvious reflected wave signals from the pile bottom which are in phase with incident wave signals. When the impedance decreases, the signals in time-domain waveform often show the same direction as those at the pile bottom. The reflective wave phase at the enlarged pile section is opposite to that of incident wave, while the wave frequency remains the same. In the case of broken and severely defective piles (except for socketed pile or piles with solid bearing stratum at pile end), the upper defect interface may witness strong positive waves while the negative ones do not occur at the lower interface.

Below are prestressed pipe piles with designed defects:

(a) β≈0.8 (b) β≈0.8

(c) β≈0.65 (d) β≈0.55

Figure 2. Defect types

Pile resistance being controlled by effective stress conditions around piles, the soil around compaction piles in saturated cohesive soil can be squeezed and reshaped to a degree that will produce excess pore water pressure, which lead to the decrease of lateral effective stress of pile and the small pile side friction. The excess pore water pressure gradually dissipates over time, while the pile side resistance increases, which is subject to the control of time factor T_h:

$T_h=4C_ht/d_2$

C_h-soil radial consolidation coefficient

T-time until piling

d-pile diameter

t-time until piling

As can be seen from the equation above, the time required to reach the maximum value of pile side resistance is inversely proportional to the square of pile diameter. The integrity detection was carried out three times: the first time with free pile and the second time after the very end of piling. One week later, several test groups conducted the third trial.

4. Pile reflection waves under different pile environments

4.1. Reflection waveform of free piles

In the case of free piles, various reflected waves at the pile end are obvious.

When β≈0.8 (Figure2 (a) (b), Pile 2 is designed), the reflected wave can hardly be distinguished at the defect position.

When β ≈0.65(Figure2 (c), Pile III is designed), the reflection at the defect is still unapparent.

When β ≈0.55 (Figure2 (d), Pile IV is designed), the reflection at the defect becomes evident.

4.2. Reflection waveform during piling

Pile length being designed according to short pile, the reflected wave at the pile end is only visible at 6 meters.

When β≈0.8 (Pile II is designed), the reflected wave can hardly be distinguished at the defect position.

When β ≈0.65 (Pile III is designed), the reflection at the defect is still unapparent.

When β ≈0.55 (Pile IV is designed), the reflection at the defect becomes evident.

4.3. Reflection waveform 7 days after piling

The waveform at the pile end maintains the same as that during piling, but the reflected wave is obviously weakened. When β ≈0.55 (Pile IV is designed), the reflection at defects attenuates likewise.

5. Results from different test groups 7 days after piling

From the results of 7 test groups, each and every group, with false negatives, could not have accurately distinguished the designed defects of model piles. A few inspection units have mistaken the second defects of Pile 3 as minor defects, which will cause quality accidents in actual detection. Other individual units have corrected the defects to two decimal places. In fact, it is neither necessary nor accurate.

The comparison between the test results and designed standard defects in each group, as shown in Table 2. The testing curves at all stages are shown in Figure 3~10.

Table 2. Summary of testing results

Defect Setting of Model Pile of Pipe Pile	Defect Type and Location of Pile 1	Defect Type and Location of Pile 2	Defect Type and Location of Pile 3	Defect Type and Location of Pile 4
	Pile 1 pile length: 16 meters	defects at 2.0 meters, Pile 2; defects at 6.4 meters, Pile 4 pile length: 9 meters	defects at 7.0 meters, Pile 3 pile length: 9 meters	defects at 6.0 meters, Pile 4 pile length: 13 meters
Test Group Number	Actual Detection Results	Actual Detection Results	Actual Detection Results	Actual Detection Results
1	defects at 2.5 meters, Pile 2	defects at 1.8, 6.0 meters, Pile 2	defects at 5.2 meters, Pile 2	defects at 6.0 meters, Pile 4
2	Pile 1	defects at 6.1 meters, Pile 3	Pile 1	defects at 6.0 meters, Pile 3
3	defects at 2.62 meters, Pile 2	defects at 2.0 meters, Pile 2; defects at 6.13 meters, Pile 3	defects at 2.8 meters, Pile 2	defects at 1.0 meters, Pile 2; defects at 5.87 meters, Pile 3
4	defects at 2.5 meters, Pile 3	defects at 1.6 meters, Pile 3; defects at 6.1 meters, Pile 3	defects at 2.8 meters, Pile 2	defects at 7.7 meters, Pile 2; defects at 6.0 meters, Pile 4

5	Pile 1	defects at 1.8 meters, Pile 2; defects at 6.2 meters, Pile 2	Pile 1	defects at 6.0 meters, Pile 4
6	defects at 3 meters, Pile 3	defects at 2.0 meters, Pile 3; defects at 6.5 meters, Pile 3	defects at 6.9 meters, Pile 2	defects at 4.0 meters, Pile 2; defects at 6.0 meters, Pile 4
7	defects at 3 meters, Pile 2	defects at 1.8 meters, Pile 3; defects at 6.1 meters, Pile 3	shallow defects, Pile 2; defects at 7 meters, Pile 3	defects at 6.0 meters, Pile 2
Notes: Pile I: complete pile shaft; Pile 2: minor defects (0.8≤β<1.0); Pile 3: obvious defects (0.6≤β<0.8); Pile 4: serious defects or broken piles (β < 0.6).				

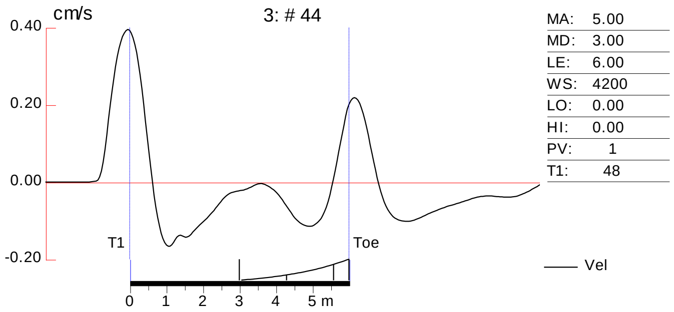

Figure 3. Waveform of pile 1 (piling)

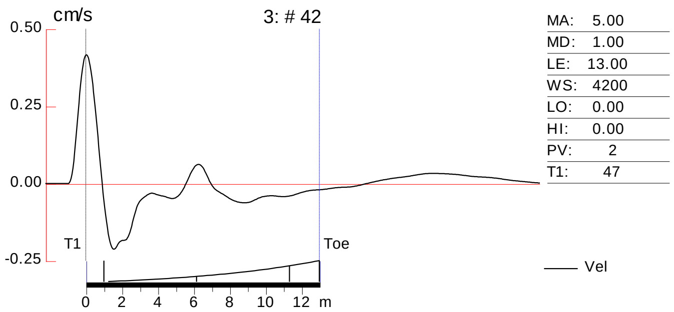

Figure 4. Waveform of pile 1 (7 days after piling)

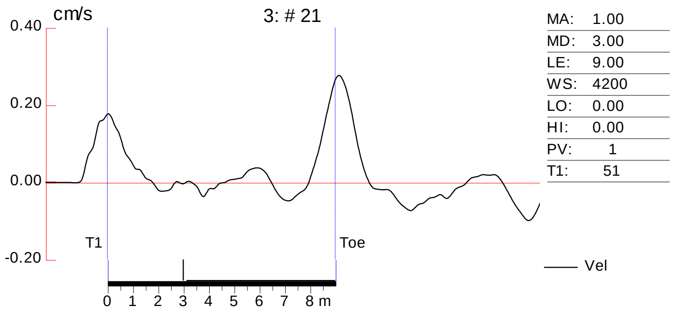

Figure 5. Waveform of pile 2 (before piling)

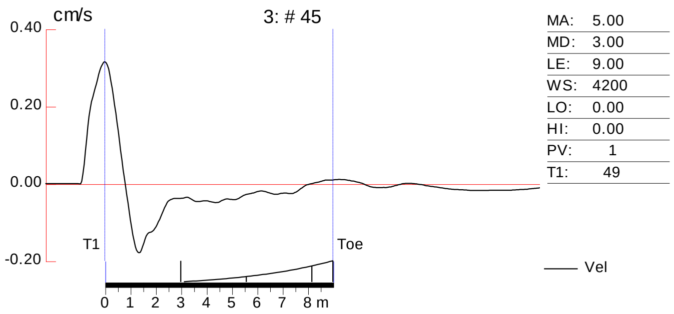

Figure 6. Waveform of pile 2 (7 days after piling)

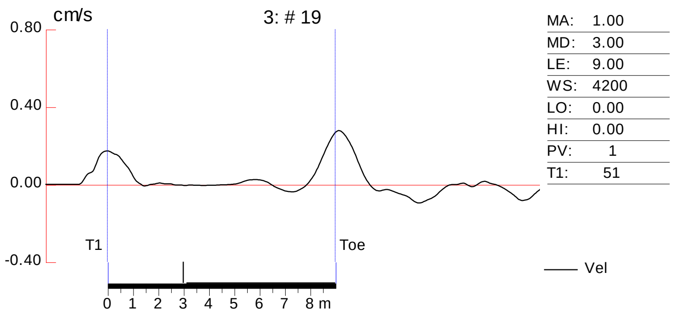

Figure 7. Waveform of pile 3 (before piling)

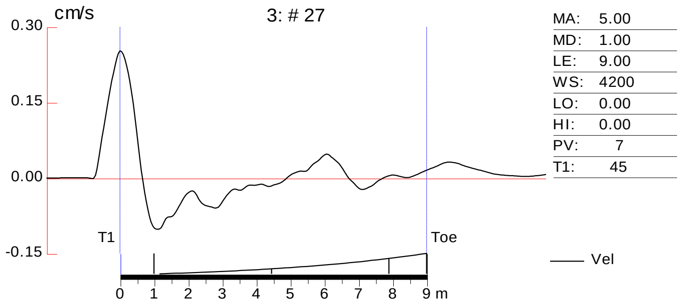

Figure 8. Waveform of pile 3 (piling)

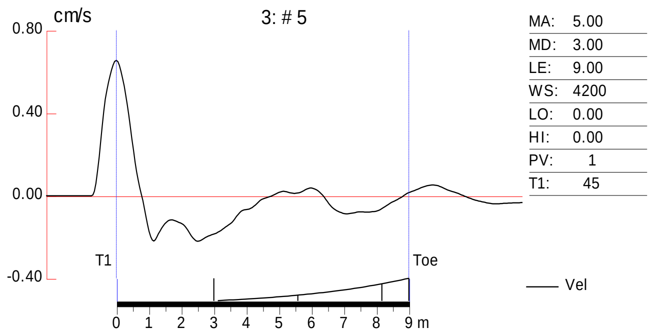

Figure 9. Waveform of pile 3 (7 days after piling)

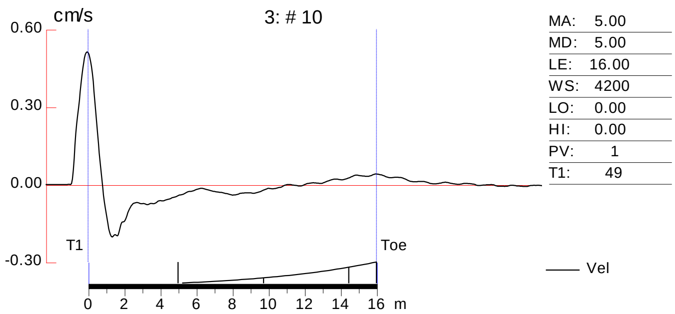

Figure 10. Waveform of pile 4 (7 days after piling)

6. Conclusions

Tests should be carried out sooner before the consolidation of the prestressed pipe pile-side and pile-end soil given less pile-side and pile-end resistance, which contributes to defect detection.

When β≈0.65, the reflection wave at detects is inconspicuous, the false positive rate being greater than 95% (only one group in 7 was classified as category 3).

When β≈0.55, the false positive rate is 100%, the test groups failed to distinguish Pile IV;

Smaller defects do not yield accurate results in the integrity test of prestressed pipe pile by reflected wave method, which could still be wrongly differentiated as Pile II even in the case of broken piles or short piles.

The reflected wave method can hardly be detected if prestressed pipe piles are damaged locally. In plastic soil, the shallow short pile has obvious reflection and vice versa.

The consolidation degree of pile end soil is sensitive to reflected wave, and the consolidation degree of pile side soil is insensitive to the reflected wave at the pile defects.

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