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Research on non-destructive testing technology for existing bridge pile foundations

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Abstract. Pile foundations of existing bridges lie in soil and water environment for long term and endure relatively heavy vertical loads, thus prone to damages, especially after stricken by external forces, such as earthquake, collision, soil heap load and etc., and the piles may be injured to certain degrees as well. There is a relatively complete technical system for quality inspection of new bridge pile foundations without structures on the top. However, there is no mature technical standard in the engineering community for the non-destructive testing technology specific to the existing bridge pile foundations. The quality of bridge pile foundations has always been a major problem that plagues bridge maintenance. On the basis of many years' experiences in test engineering and theoretical studies, this study developed a new type of detection technology and equipment for the existing bridge piles.

Keywords: existing bridge; pile foundation; non-destructive testing; bridge maintenance

1. Introduction

Catal (2014) has stated that the pile foundation is an important part of bridges and is essential for safe operation and security of bridges. As a hidden project, bridge piles may be affected by various factors, such as breakage, necking, flaring and hole defects, as described by Z Kuyumcu and S Ates (2012). Some accident cases of existing bridges in recent years showcase the grim situation of bridge safety; especially under the conditions of long-span, earthquake and horizontal force of waves, the entire bridges may collapse due to failure of pile foundation, as described by Dewaikar and Mutgi (2011). To ensure the safe operation of bridges, the bridge pile disease detection service attracts widespread attention. Dong and Zhang (2014) have pointed out that traditional visual inspection technologies are unable to meet the demands of internal structures for the concrete disease diagnosis. Conducting related researches on existing bridge piles' disease detection is an explosive subject. Relevant publications (Kuyumcu 2012, Prezzi and Basu 2009) have shown that it has become one of the research hotspots to explore some effective methods for detecting defects in bridge piles in

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service.

Ye and Yang (2010) have concluded that conditions for existing bridge piles' non-destructive detection are much more complex than the situation of free piles. Existing bridge piles are connected with upper parts of structures, such as pier, beam, cap, and etc. That will strongly interfere in reflection of the stress wave, resulting in more complex detection signals, and thus increasing the difficulties in analyses and judgments. Therefore, the existing bridge piles' inspection is still a technical problem in engineering. This study proposes a technology based on the reflected wave method to detect the integrity test of in-situ bridge pile foundations. In this method, vibrations are applied to the top of the cover beam and the top of the cap. The quality of piles is determined by analyzing the received reflected stress wave signals. Simple, fast and economic, this method does not cause damages to piles and thus can be widely used.

This study compared the results of the reflected wave detection method and the coring detection method based on engineering examples, verifying the feasibility of the reflected wave detection method to detect defects of pile foundations. And after conducting numerical simulation of the method, this study grasped the stress propagating routes and provided field testing techniques and recommendations for sensor arrangement points.

2. Research on a new non-destructive method for existing bridge pile foundations

Zhang (2009) has pointed out that due to the existence of pile caps, columns, cap beams and other structures in the bridge pile foundations, the traditional reflected wave method cannot detect and analyze them. In this study, the propagation path of the reflected wave is explored according to different excitation positions, and the influence of the pile top structure on the transmitted wave signal is understood. The filtering technique is used to eliminate the influence, so as to inspect the integrity of the in-service bridge pile foundations.

2.1 Exciting on top of the cap beam

It can be seen from Fig. 1 that when the stress wave caused by the excitation propagates in the cap, it is easy to form multiple reflections locally, thereby forming an interference signal.

Assume that the height of the cap beam is *H*, the height of the pier column is *L*, the height of the cap is *M*, the radius of the pillar portion is *R*, the radius of the pile foundation is *R1*, and the distance between *m* point and *f* point is *X*. Then, the incident angle θ of the incident wave propagating to the bottom of the cap is

$$\sin\theta = \frac{H+L+M}{\sqrt{(H+L+M)^2+(R_1+X)^2}} \tag{1}$$

Then, the stroke N of the reflected wave (such as *ef* and *mk*) in the cap is

$$N = \frac{M}{\sin\theta} = \frac{M\sqrt{(H+L+M)^2+(R_1+X)^2}}{H+L+M} \tag{2}$$

The reflected wave is reflected twice in the cap, that is, after two reflection strokes (2N), a reflection period is formed. Assume that the longitudinal wave velocity of the concrete of the bearing platform is c; then the reflection frequency is calculated as follows

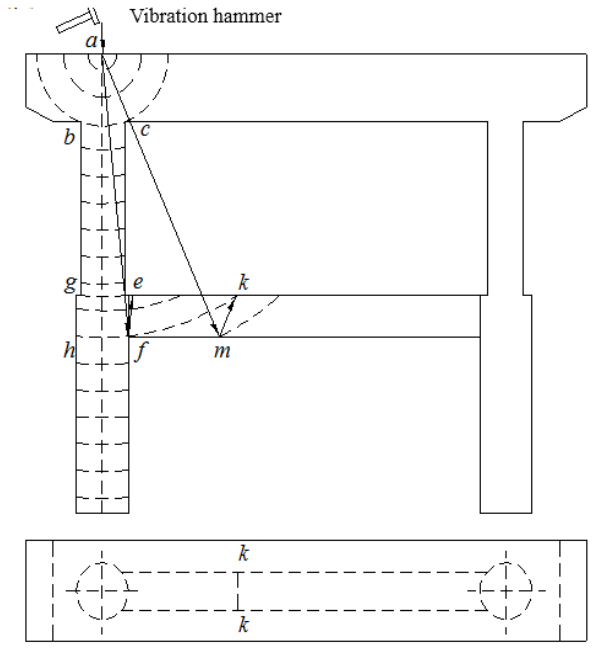


Fig. 1 Diagram of stress wave propagation caused by excitation

$$T = \frac{c}{2N} = \frac{c(H+L+M)}{2M\sqrt{(H+L+M)^2 + (R_1 + X)^2}} \tag{3}$$

As shown in Fig. 1, when the incident wave is reflected near the point *f*, due to the large incident angle, multiple reflections near the point *f* are easily formed, thereby forming a pseudo-shear excitation to the pile foundation.

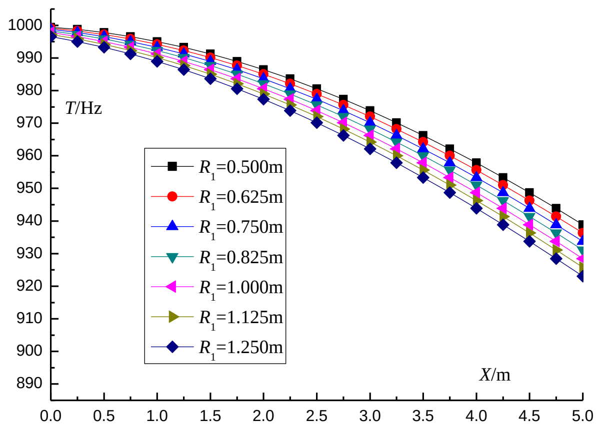


Fig. 2 *T* and *X* relation chart (R_1 changes, $c = 3000$ m/s , $D = 15$ m , $M = 1.5$ m)

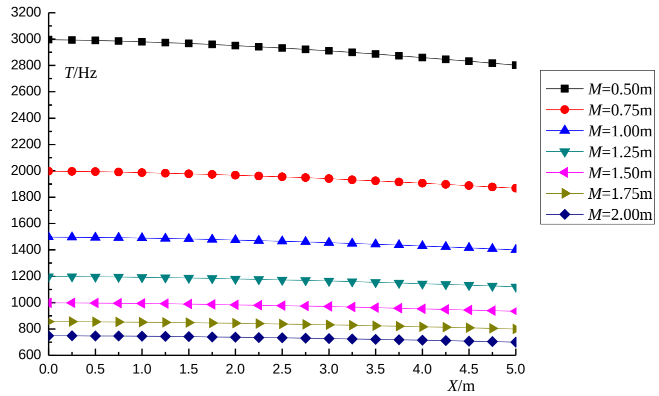


Fig. 3 T and X relation chart (M changes, $c = 3000\text{m/s}$, $D = 15\text{m}$, $R_1 = 0.75\text{m}$)

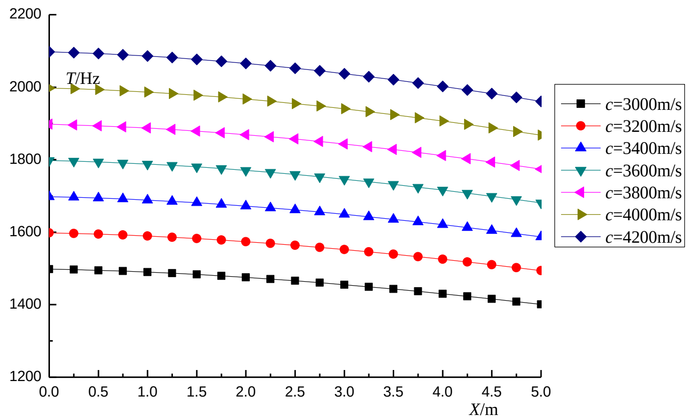


Fig. 4 T and X relation chart (c changes, $M = 1.0\text{m}$, $D = 15\text{m}$, $R_1 = 0.75\text{m}$)

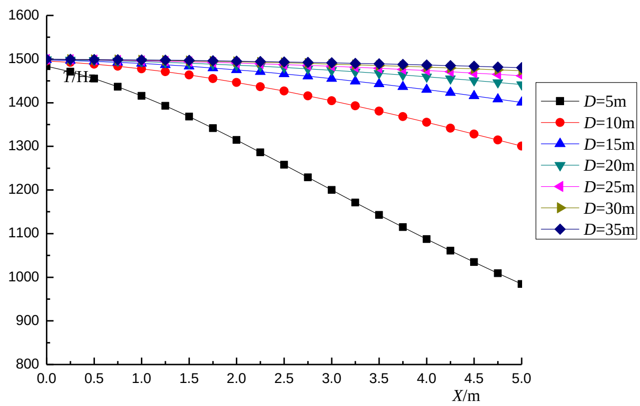


Fig. 5 T and X relation chart (D changes, $M = 1.0\text{m}$, $c = 3000\text{m/s}$, $R_1 = 0.75\text{m}$)

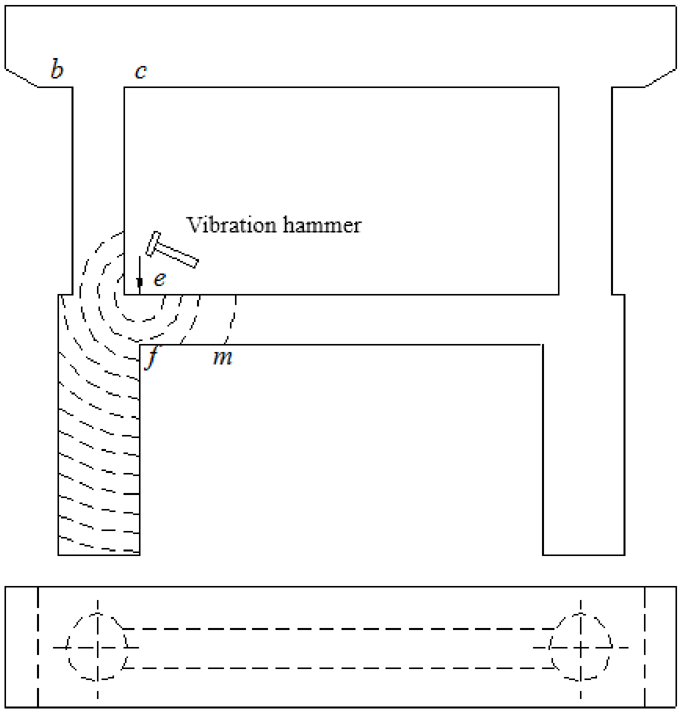


Fig. 6 Exciting on top of the joint between the cap and the pile

Assume $D = H + L + M$, and let *D* vary between 5 m and 35 m, *m* between 0.75 m and 2.0 m, *c* between 3000 m/s and 4200 m/s, R_1 between 1.0 m and 2.5 m, and *X* between 0.0 and 5.0 m. According to Formula (3), the curve of *T* can be obtained as shown in Fig. 2 to Fig. 5.

2.2 Exciting on top of the joint between the cap and the pile

As shown in Fig. 6, the height of the platform is *M*, the radius of the pillar portion is *R*, the radius of the pile foundation is *R1*, and the distance between the points *m* and *f* is *X*. Therefore, the travel *N* of the reflected wave in the cap is

$$N = \sqrt{M^2 + (R_1 - R + X)^2} \tag{4}$$

Then the stress wave reflection frequency T in the cap is

$$T = \frac{c}{2N} = \frac{c}{2\sqrt{M^2 + (R_1 - R + X)^2}} \tag{5}$$

Assume $D = R_1 - R$, and let *D* vary between 0.05 m and 0.20 m, *M* between 0.75 m and 2.0 m, *c* between 3000 m/s and 4200 m/s, and *X* between 0.0 and 5.0 m. According to Formula (4), the variation curve of *T* can be obtained as shown in Fig. 7 to Fig. 9.

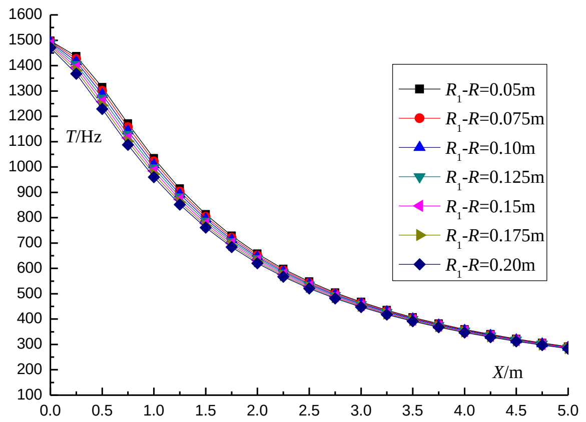


Fig. 7 T and X relationship diagram (D changes, M = 1.0 m, c = 3000 m/s)

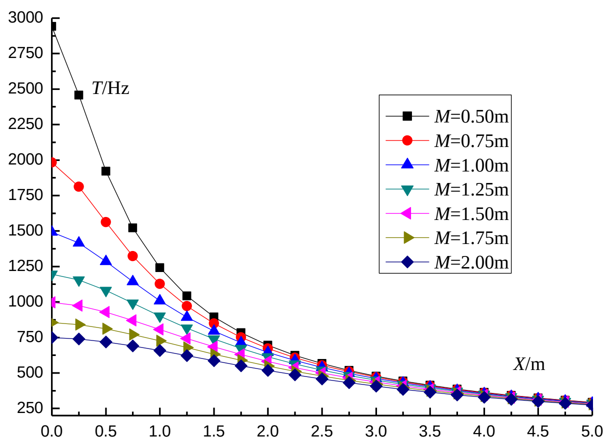


Fig. 8 T and X relationship diagram (M changes, D=0.10 m, c=3000 m/s)

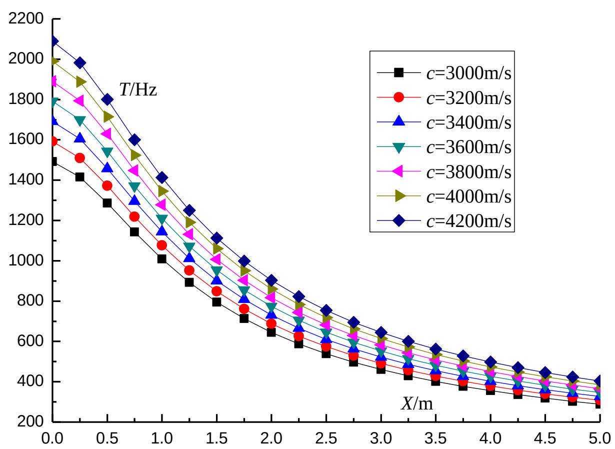


Fig. 9 T and X relationship diagram (c changes, D=0.10 m, M=1.0 m)

Fig. 10 Multi-channel reflected wave pick-up device

It can be seen from Fig. 7 to Fig. 9 that the reflection frequency of the reflected wave at the edge of the platform is relatively high, and the lateral step ΔX of the reflected wave shifted to the other side of the pier is

$$\Delta X = R_1 - R + X \tag{6}$$

It can be found from Equation (7) that when the incident wave is reflected from the edge of the cap, the moving step of the reflected wave is small, and multiple vertical excitations at the joint between the cap and the pile will be formed.

3. Research and development of equipment

In this study, a multi-channel reflected wave pick-up device was developed to inspect the pile foundations of in-service bridges. By using this device, the data on pile foundations, tie beams and columns are all collected and tested simultaneously. A set of software is used to realize the synchronized analysis and processing of multi-channel data, ensuring the consistency of multi-channel data analyses. A multi-channel signal processing module is used to filter the interference waves, so as to deliver accurate detection of in-service pile foundations.

4. Numerical simulation analysis of the new non-destructive method for bridge pile foundations

Several numerical approaches were developed to analyze the responses of laterally loaded piles in the past. Osman and Randolph (2011) presented a closed-form analytical solution for the

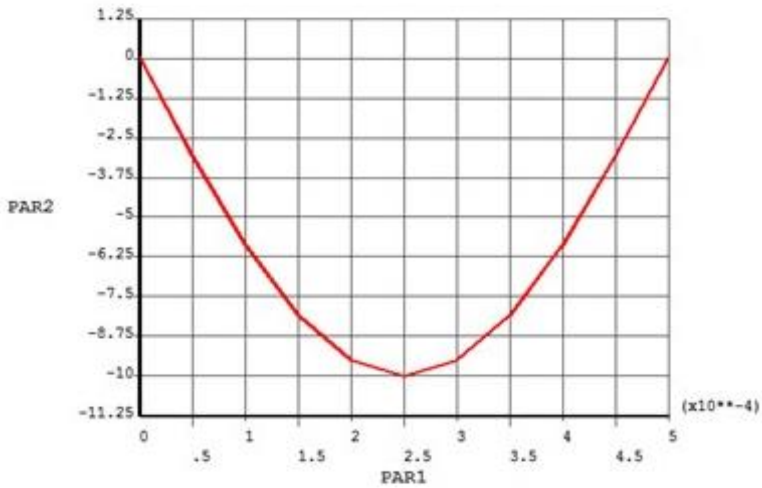


Fig. 11 Pulse hammering loads

consolidation of soils around a laterally loaded pile under plane strain conditions by assuming elastic deformation of soil. Sanjay (2012) showed that the three-dimensional finite element analysis (FEA) was one of the precise analysis methods.

The finite element ANSYS / LS-DYNA was used to conduct numerical simulation test of defects in pile foundations of existing bridges. The single soilless pile model, the single soil pile model and the existing bridge pile foundation model were established to study the force transmission routes in existing bridge pile foundation model under the pulse hammering loads, so as to provide a basis and reference for the analysis and measuring points of existing pile foundations' detection. The computing model used cosine pulse hammering force load, as shown in Fig. 11.

In order to verify the reflected wave method in pile foundations of existing bridges and to comparatively analyze the position arrangement of sensors, numerical simulation analyses for common defects (necking reduced, and cavity) were delivered.

4.1 Computing model

A computing model simulated the necking reduced and cavity defects. And then different positions and extents of defections were compared and analyzed. All defection models are shown in Table 1. And Models 1 and 4 were shown in Figs. 12 and 13, respectively.

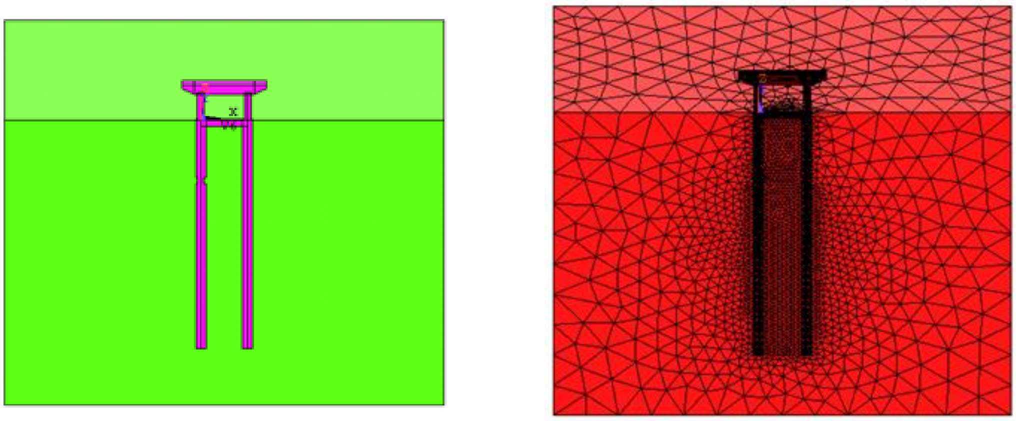
4.2 Analysis of computing results

Apply the same pulse loads to the top of the piles of Models 1~ 4, and receive the wave speed signals from the top of the piles and the side of the columns. The computing results of Model 1 and Model 4 were shown in Figs. 14 and 15.

As can be seen from the computing results, the seed signal curve starting from the top of the pile is sensitive to pile bottom reflection and such defects as necking reduced and cavity; however, due to reflection at the top of the cap beam, it is difficult to determine whether the reflection signal comes from defects or from the cap beam when receiving the speed signals from the side of the piles.

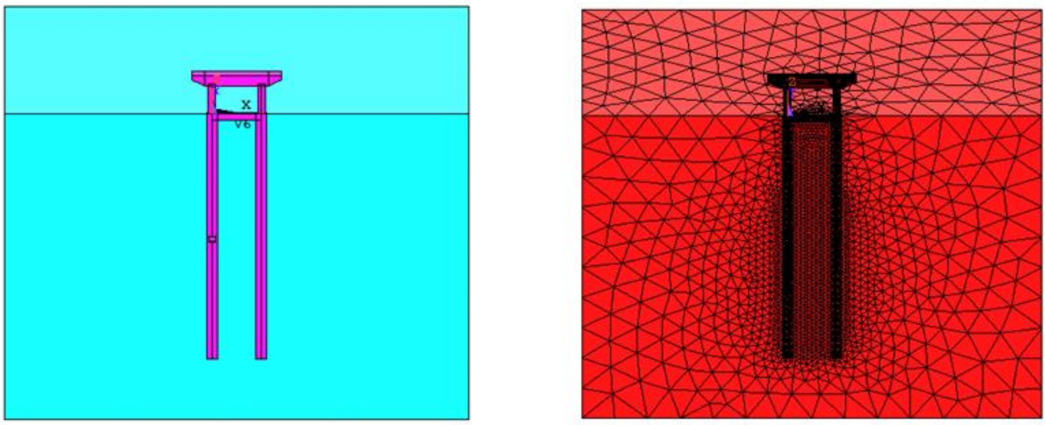
Table 1 Model defects

Defect type	Model No.	Defect position and extent
Necking reduced	Model 1	From the top of the pile at 10 m on the left: necking reduced 25cm
	Model 2	From the top of the pile at 20 m on the left: necking reduced 35cm
Cavity	Model 3	From the top of the pile at 10 m on the left : a 100cm height, 60cm diameter cavity
	Model 4	From the top of the pile at 20m on the left : a 100cm height, 80cm diameter cavity



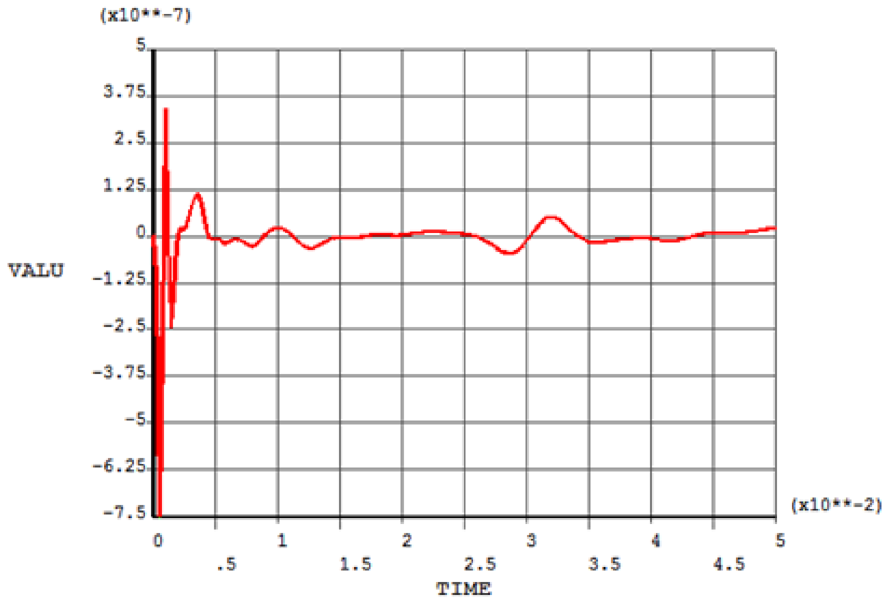
(a) Model diagram (b) Meshing model diagram

Fig. 12 Calculation Model of Model 1

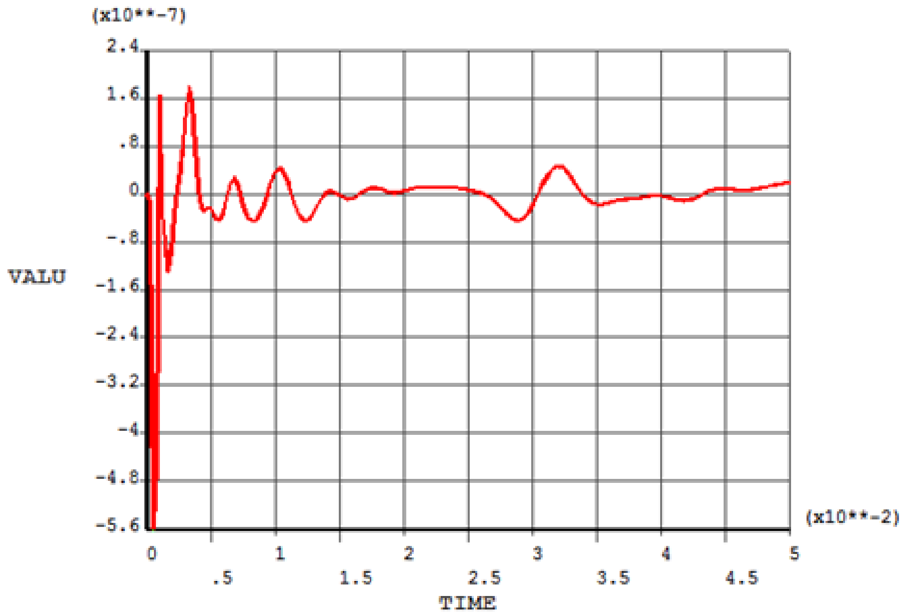


(a) Model diagram (b) Meshing model diagram

Fig. 13 Calculation Model of Model 4

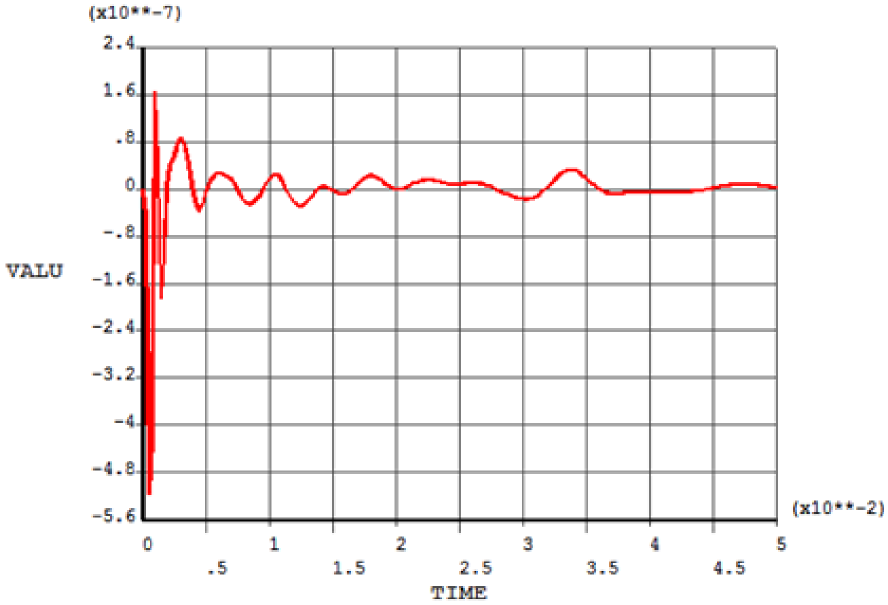


(a) Signal received from the top of the pile

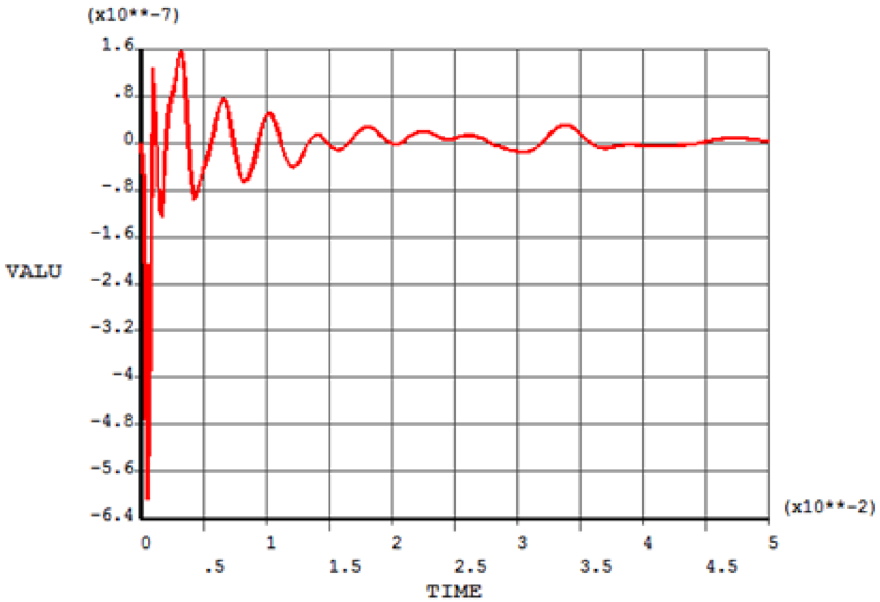


(b) Signal received from the side of the pile

Fig. 14 Model 1 received Vz (speed) signal curve



(a) Signal received from the top of the pile



(b) Signal received from the side of the pile

Fig. 15 Model 4 received Vz (speed) signal curve

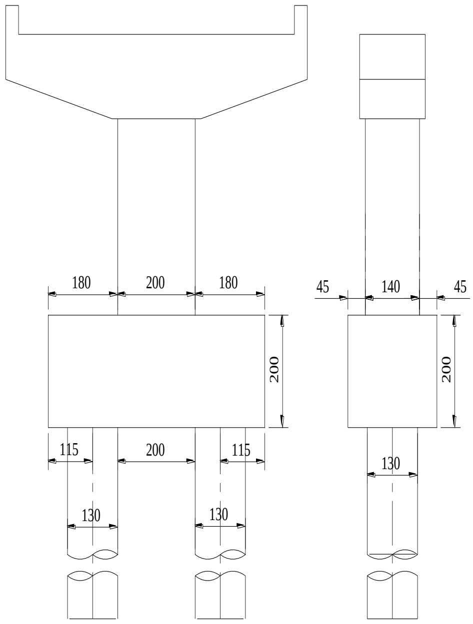


Fig. 16 Structure of 5# pile of ramp bridge (unit: cm)

5. Field test

5.1 General condition of bridge

Pile foundation test was conducted at a girder bridge. There were two pile foundations to be tested, which have a design length of 39 m and a design diameter of 1.3 m. Before the test, the cap beam, pile columns and etc. were constructed, with a typical structure of 5# pile of Bridge H, as shown in Fig. 15.

According to results of geological survey reports, the composition of the soils at the location of 5# pile foundation is: silt and sand at the upper part; silt clay soil at the middle part; and circular gravel and pebbles at the lower part.

5.2 Test research

Apply vibrations to the pile foundation from corresponding locations on the top surface of bridge cap beam and detect the waves. See Figs. 16 and 17.

The detection results of H5-1# pile are shown in Figs. 18 and 19, and the detection results of H5-2# pile in Figs. 20 and 21. It can be seen that the two reflected wave curves are similar, and the wave velocities are normal. And both of them get a clear reflection from the bottom of pile foundations, as shown in the testing results. Pile diameter expanding signal was found in the position 9m below the top surface of H5-1# cap beam. However, abnormal signal was found in the position 10m below the top surface of H5-2# cap beam.

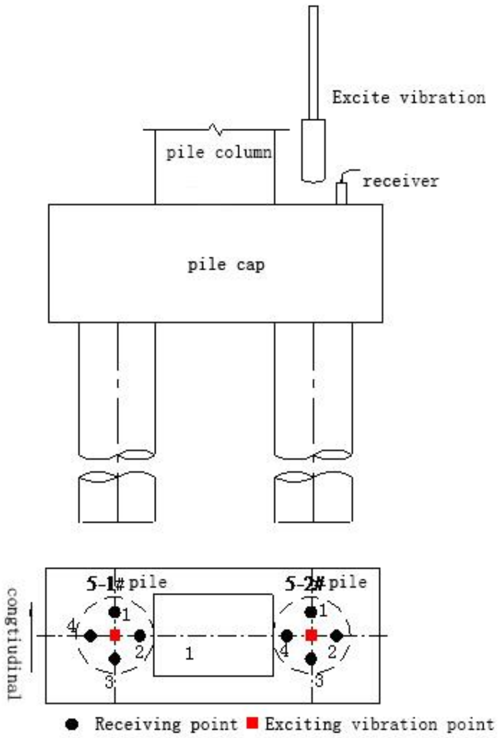


Fig. 17 Schematic diagram for the vibration-exciting locations and signal-collecting locations in the reflected wave method

Fig. 18 Field test photo

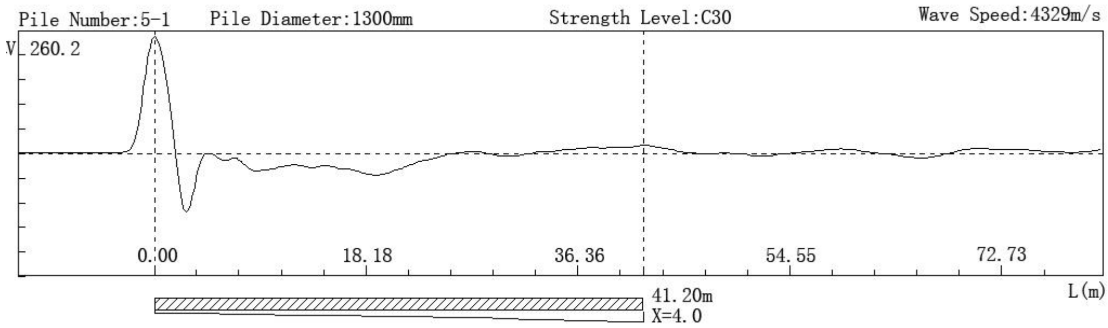


Fig. 19 H5-1# pile detection curve (Receiving point 1)

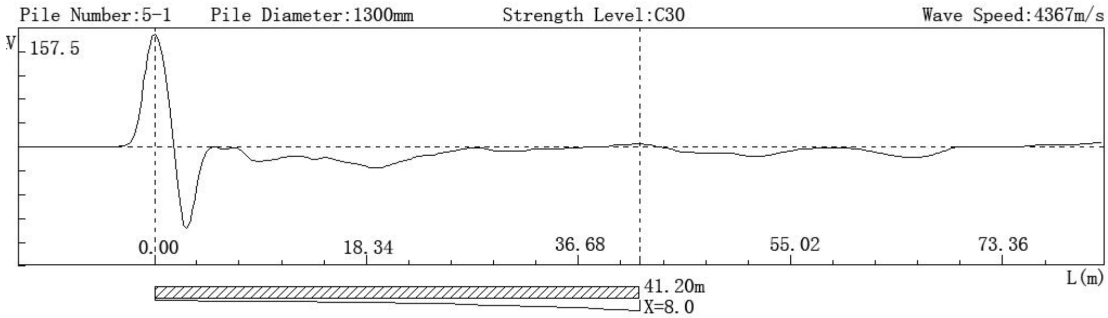


Fig. 20 H5-1# pile detection curve (Receiving point 2)

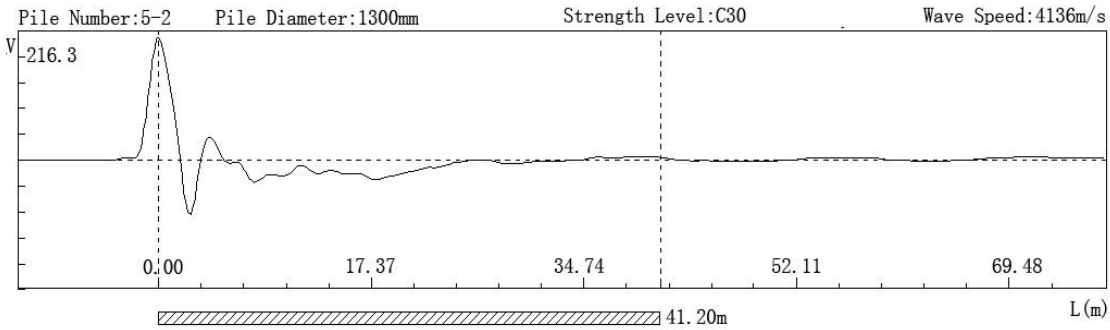


Fig. 21 H5-2# pile detection curve (Receiving point 3)

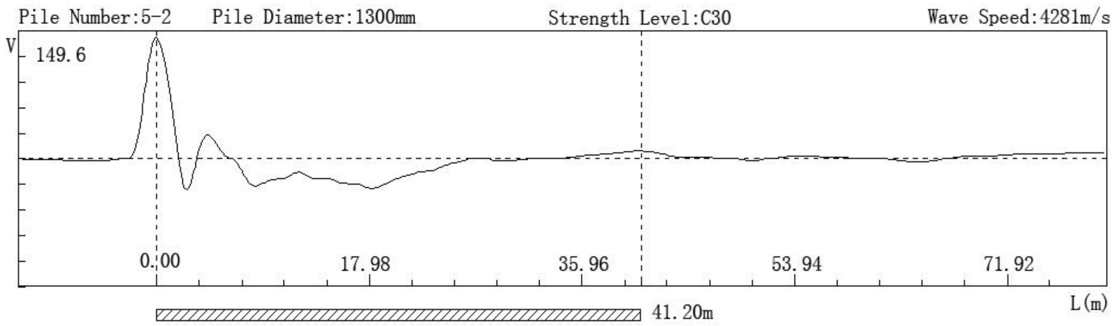


Fig. 22 H5-2# pile detection curve (Receiving point 4)

6. Conclusions

The following conclusions are drawn from above field tests and numerical simulation analyses:

(1) It is feasible to detect the pile foundations of bridges in service by using the reflected wave method;

(2) When hammering the top surface of a pile, compressive stress wave propagates to the bottom of the pile and, at the same time, tensile stress wave propagates along the columns to cap beam and then reflects at the top of the cap beam;

(3) Stress wave propagates less to the tie beam, the impact on which therefore can be ignored in field tests;

(4) Reflection at the bottom of a pile can be detected obviously by analyzing the velocity and acceleration signals received at the top of the cap beam, the top of the pile and the side of the column, thus verifying the feasibility of using reflected wave method to detect pile foundations of existing bridges;

(5) It is not recommended to receive the reflection signals at the top of the cap beam, because the reflection wave signals' curves will oscillate when receiving the signals at the top of the pile, a phenomenon which is unfavorable for recognizing the defect reflection signals from pile foundations;

(6) It is found that the reflection signals of defects at different positions and the reflections at the bottom of piles are strong by conducting numerical simulation analysis of common defects (necking reduced, necking expanded, and cavity) in pile foundations of existing bridges as well as receiving the reflection signals both from the top of piles and from the side of columns. So the feasibility and reliability of using the reflected wave method to detect pile foundations of existing bridges is verified;

(7) The detection of pile foundations of existing bridges shall try to avoid receiving signals from the side of the column and, when possible, to put sensors on the top surface of piles.

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