

Integrity testing of piles in platform-pile systems

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ABSTRACT: The wave propagation in platform-pile systems with one or more piles is studied by the numerical simulations and model tests. There are multiple reflections in the platform. The waves transmitted across the interface between the platform and the pile are consecutive, not in the form of a single pulse. The reflections from the pile body are obscured by the multiple reflections in the platform. If there are two or more piles in platform-pile systems, the response of the platform surface over the tested pile will be contaminated by the reflections from neighbouring piles. Since the response of the platform is disturbed by the multiple reflections in the platform and the neighbouring piles, the reflections from the tested pile body are not easily identified from the response of the platform surface over the tested pile. By using the filtering technique and comparison of responses over the tested pile and the known intact pile in the same platform-pile system, accuracy of the integrity testing of piles can be improved. The two-station measurement is also suggested for the integrity testing of piles in platform-pile systems.

1 INTRODUCTION

The impact-echo method is widely used in a single pile integrity testing. In this method, piles are assumed as bars. Based on one dimensional stress wave theory, the variation degree and range of pile impedance can be estimated from the particle velocity response measured on the top of piles (Middendorp and Reiding 1988, Starke and Janes 1988, Rausche et al. 1992). However, piles used in slope protection of deep foundations, bridges and docks are usually connected with a platform. The pile anomalies or damages such as necking, bulging, contaminating, breaking and crack may be generated by construction, impact or earthquakes, so the integrity testing of piles in platform-pile systems is important. The integrity testing of piles in platform-pile systems by impact-echo is more complex than that in a single pile. Firstly, the out-going waves generated by the source, such as the dilatational (P), transverse (S) and Rayleigh (R) waves, are repeatedly reflected in the platform, the response of the platform surface to the reflections from the beneath pile body is obscured by the multiple reflections. Secondly, since the waves transmitted across the interface of the platform and the pile into the under pile are consecutive, the reflections from the pile body are not in the form of a single pulse. Lastly, the response over the test pile is contaminated by the reflections from the neighbouring piles. In this work, effects of the platform on the integrity testing of

piles are studied by the numerical simulations, model tests and in-situ tests.

2 NUMERICAL SIMULATIONS

The waves generated by the impact source acted on the surface of a platform are the P-, Von-Schmit (or Head), S-, and R-waves as shown in Fig. 1. Energy of the Von-Schmit waves is concentrated in shallow area below the surface (Rose 1999). The response of the surface is mainly controlled by the P-, S- and R-waves. When the propagating distance along the surface is small relative to the pulse width, which is defined as a product of the time duration and the bar velocity, the direct traveling P-, S- and R-waves are superposed together. These waves are repeatedly reflected from the boundaries of the platform, part of waves are transmitted into the beneath pile. Energy of the reflected and the transmitted waves is related to the thickness of the platform and the ratios of the platform to the pile in Young's modulus and the cross section. When there are impedance variations in pile body, the transmitted waves are reflected from the variation positions. The phase of the first reflection is in phase or out phase in 180° with the incident waves according to decrease or increase of the pile impedance. The wave propagation paths in a platform and a pile are demonstrated in Fig. 2. The models, which are comprised of a platform and a pile,

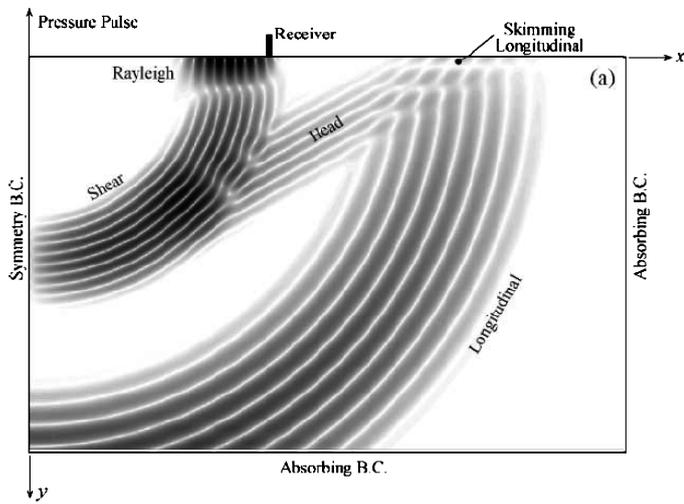


Figure 1. The wave patterns generated by the impact pulse (after Hassan and Veronesi 2003).

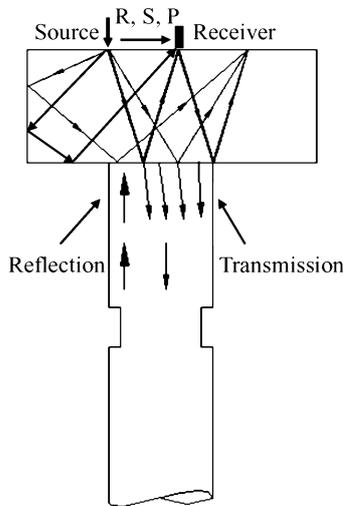


Figure 2. Wave propagation in the platform-pile system.

are used to investigate effect of the platform on the response of the surface. The platform is $1.0 \times 1.0 \text{ m}^2$ in cross-section and 0.5 m in thickness. The pile is $0.2 \times 0.2 \text{ m}^2$ in cross-section and 2.0 m in length. The bottom of the platform and the top of the pile fully contact and their centroidal axes coincide together. Poisson's ratio of 0.25, Young's modulus of 40 GPa and the density of 2500 kg/m^3 are taken for the platform and pile materials.

The program ANSYS/LS-DYNA is used to simulate responses in platform-pile systems. The models are discretized with at least ten elements per wavelength. Effects of soil on wave propagation are not considered in this study. Both the platform and the piles are free.

2.1 Effect of the reflections from the sides

Because the waves transmitted into the pile are not in the form of a single pulse. The waves which are consecutively reflected from the variations of pile impedance can not be separated from transmitted waves. The responses of the surface to the consecutive reflections from pile impedance variation are also contaminated by multiple

reflections in the platform, as shown in Fig. 3. The dashed and solid lines are corresponding to the surface and the pile skin at position of 1 m below the surface respectively. The responses for the case in which the non-reflecting boundary conditions are applied to the sides to prevent the reflections from the sides are given in Fig. 4. By comparing the responses shown in Figs. 3 and 4, it can be seen that the reflections from the free tip are obscured by those from the sides.

2.2 Effect of the thickness

Because of the geometric spreading of the wave front, energy of waves attenuates. The thinner the thickness of the platform is, the less the geometric attenuation of the waves is and the larger the energy intensity of waves incident on the interface is. Thus, the intensity of reflections from the pile body increases. Since the area of the sides decreases, energy of reflections from the sides decreases. If the thickness is reduced from 0.5 m to 0.2 m, the reflections from the tip are obvious both in the responses of the surface and of the skin, as shown in Fig. 5.

2.3 Effect of the neighbouring piles

If there are two or more piles in a platform-pile system, the outgoing waves from the source over the tested pile can be transmitted into the neighbouring piles through the platform. As the neighbouring pile impedance

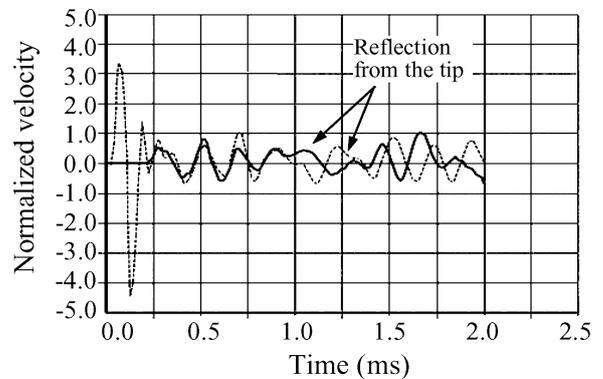


Figure 3. Effects of the reflections from the sides on the responses.

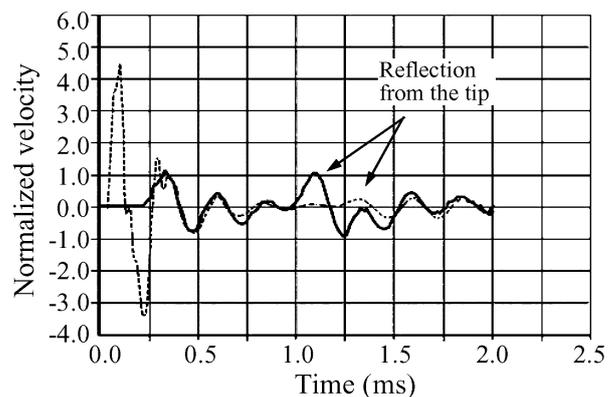


Figure 4. The responses of the surface and the skin without reflections from the sides.

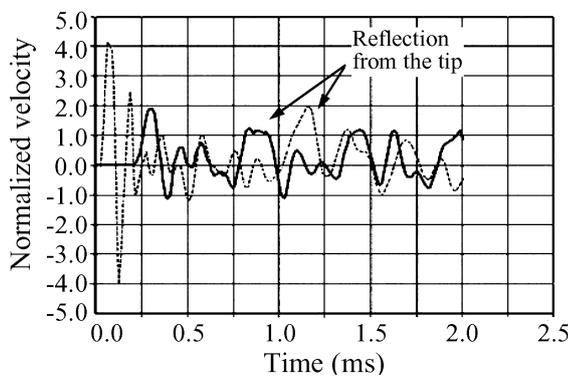


Figure 5. Effects of the thickness on the responses.

varies, the transmitted waves will be reflected from the variations and the reflections propagate back into the platform. Thus, the response over the tested pile can be contaminated by the reflections from the neighbouring piles. In order to study effects of the reflections from the neighbouring piles, two piles are contained in the platform-pile model, as shown in Fig. 6.

Two piles are $0.2 \times 0.2 \text{ m}^2$ in section. One is 3 m in length and the shorter one is 1 m in length. The platform is $1.0 \times 1.0 \text{ m}^2$ in section and 0.2 m in thickness. The interval distance between centroidal axes of piles is 0.3 m. To diminish the reflecting from the sides of the platform, non-reflecting boundaries are applied to the sides. Poisson's ratio of 0.25, Young's modulus of 40 GPa and the density of 2500 kg/m^3 are set for the platform and the pile materials. The reflections from the shorter pile tip can be seen in the responses of the surface over the longer pile as well as of the skin of the longer pile. The simulation results in Fig. 7 show that the reflections from the neighbouring piles must be taken into consideration for integrity testing of piles in platform-pile systems.

3 MODEL TESTS

A group of model piles were cast for the quantitative integrity analysis of piles. The piles were buried into the ground and the tops are 0.5 m from the ground surface. Two years later, two of the piles were connected by a plate. One is intact, the other one is necked. Piles are $0.15 \times 0.15 \text{ m}^2$ in normal cross-section and 3.3 m in length. The necked part, which is $0.09 \times 0.09 \text{ m}^2$ in section, is in the range from



Figure 6. The platform-pile with two piles.

2.5 m to 2.8 m. The dilatational velocities of the piles are in the range from 3500 m/s to 3800 m/s. The geometric sizes of the platform-pile system are shown in Fig. 8.

An accelerometer is mounted on the surface of the plate over the intact pile and the necked pile by the glue respectively. A hammer impacts the surface near the receiver. The typical responses of particle velocity are shown in Figs. 9a and 9b.

Because the piles and the plate are not cast in the same time, the piles and the plate are not fully coupled. The multiple reflections from the interface are strong. Since the peak corresponding to each reflection from the interface gradually decreases with the number of reflection, when there are the reflections from the necked pile, the peak of the reflections from the interface may more or less increase because of constructive interference of the waves. The reflections from the necked position and the tip can be identified from the response over the necked

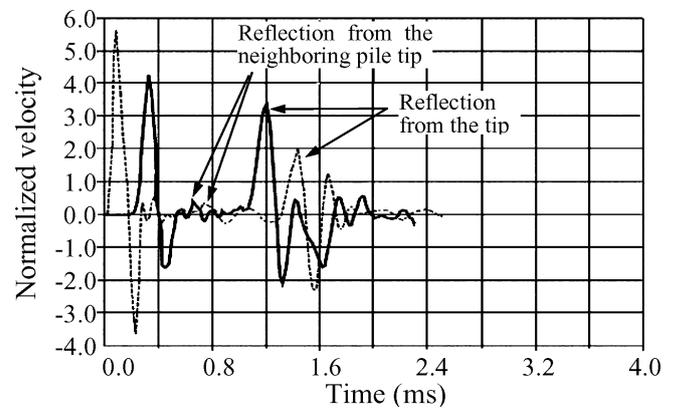


Figure 7. Effects of the reflections from the neighbouring pile on the responses.

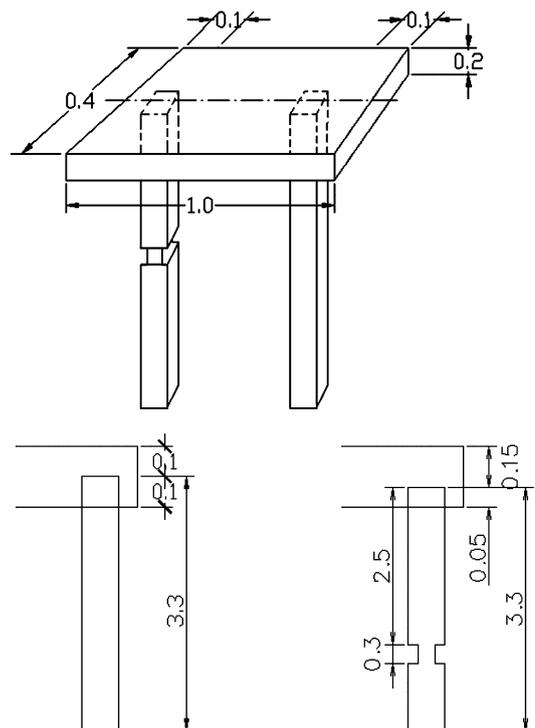
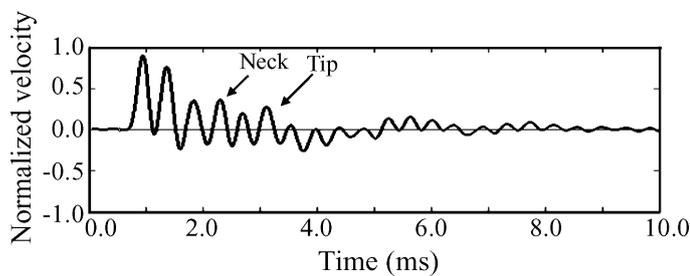
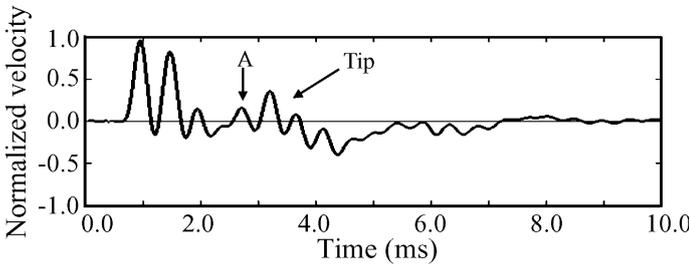


Figure 8. Layout of the model (unit in m).



(a)



(b)

Figure 9. The particle velocity responses of the surface (a) over the necked pile and (b) over the intact pile.

pile. In the response over the intact pile, the peak of the reflections at the time marked by A increases after attenuation of the multiple reflections. According to the arrival time of the reflections, the reflections from the necked pile probably arrive at the time marked by A.

4 IDENTIFICATION OF THE REFLECTIONS

Since the reflections from the pile body are obscured by the multiple reflections in the platform, it is necessary to diminish the interfering reflections by means of signal processing techniques or to identify the reflections from the pile by comparing responses.

4.1 Filtering

Because energy of the multiple reflections in the platform gradually attenuates with the number of reflection, when the reflections from the pile body take more time to reach the surface, the multiple reflections will die away before the arrival of the reflections from the pile body. Since the fundamental resonant frequency of the multiple reflections is higher than that of the reflections from the pile body. The multiple reflections can be diminished by low-pass filtering. It is possible to identify the reflections from piles by filtering the response of the surface.

A slope protection pile is 16 m in length, 0.6 m in diameter. The pile was connected with the others by a long plate, which is 1.0 m in width and 0.4 m in thickness. The response signal measured on the plate is filtered by low-pass frequency of 2000 Hz. The reflections from the tip can be found from the response shown in Fig. 10. However, if the resonant frequencies of reflections from the pile body are high, energy of the reflections from the pile body can be also

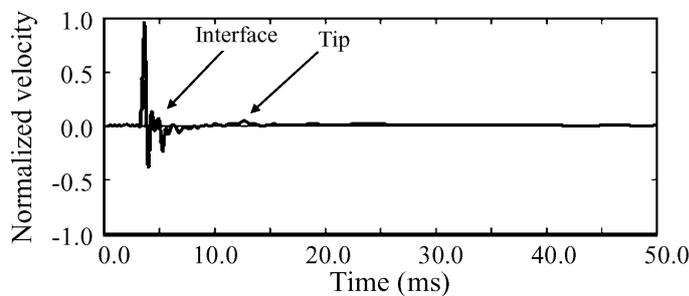


Figure 10. The response measured on an in-situ pile.

diminished by the low-pass filtering. Moreover, the phases of the response may be changed by inadequate low-pass filtering and the integrity of piles may be misjudged.

4.2 Comparison of the responses

If the same measuring conditions, such as the source and the receiver, are used for different piles in the same platform-pile system, influences of the multiple reflections in the platform on the responses over different piles are similar. The differences between the responses are mainly generated by reflections from the pile body. When the responses over the known intact pile and the suspected pile are obtained, the reflections from the suspected pile may be found by comparing two responses. The responses given in Figs. 9a and 9b are compared in Fig. 11. The result shows that the reflections from the necked part can be identify by comparing the responses over the neck and intact piles.

4.3 Two-station measurement

Since the response over the tested pile is influenced by the reflections from the neighbouring piles, whether the reflections are from the suspected pile can not be identified by filtering technique or comparison of responses. The two-station measurement is tried to solve this problem.

Two accelerometers are mounted on the surface of the platform and on the skin of the pile respectively, as shown in Fig. 12. Because the dilatational waves dominate the transmitted and reflected waves, other types of waves are ignored in the transmitted and reflected waves. Assuming that h_0 is the thickness of the platform, h_1 is the distance between the interface and the receiver on the skin and c_{p0} and c_{p1} are the

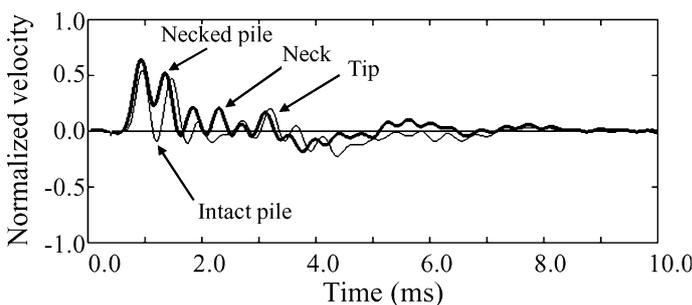


Figure 11. Comparison of the responses over the necked and intact piles.

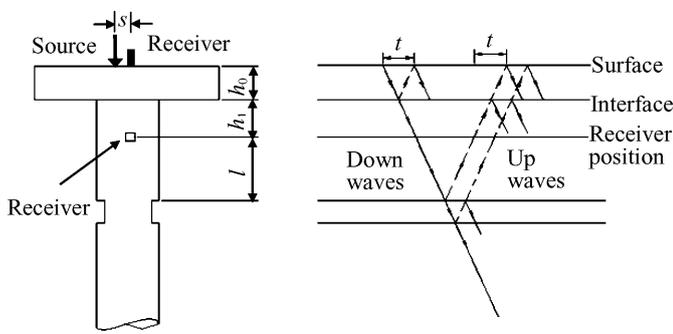


Figure 12. Schematic of two-station measurement.

average velocities of waves in the platform and the pile respectively, the time for the waves traveling from the source to the receiver on the skin (the second receiver) is

$$t_1 = h_1/c_{p1} + h_0/c_{p0} \quad (1)$$

Since s , the distance between the source and the receiver on the surface (the first receiver), is much smaller than $h_0 + h_1$, the distance between the source and the second receiver, the time for the waves traveling from the source to the first receiver can be omitted. The time interval between the first arrivals at the first and second receivers is approximated to

$$\Delta t_T = h_1/c_{p1} + h_0/c_{p0} \quad (2)$$

As the down-going waves are reflected and transmitted from and across the interface, the traveling time for the reflections back to the surface is h_0/c_{p0} and the time for the transmitted wave arrival at the second receiver is h_1/c_{p1} . The time interval is

$$\Delta t_{TR} = h_1/c_{p1} - h_0/c_{p0} \quad (3)$$

The expression (3) indicates that the response time of the first receiver is prior to or lags behind the response time of the second receiver and the time interval is much less than that between the first arrivals.

Assuming that the pile impedance varies at a position l from the second receiver, the waves will be reflected from the position. The up-going waves first arrive at the second receiver and then the waves transmitted across the interface without the phase changing arrive at the first receiver. The time interval is

$$\Delta t_R = h_1/c_{p1} + h_0/c_{p0} \quad (4)$$

It can be found that if the reflections are from the pile body, the time interval is equal to that between the first arrivals. Thus, the multiple reflections in the platform can be excluded and the reflections from the pile body can be identified by comparing the time interval between in-phase responses of the first and second receivers to the reflections with the first arrival interval.

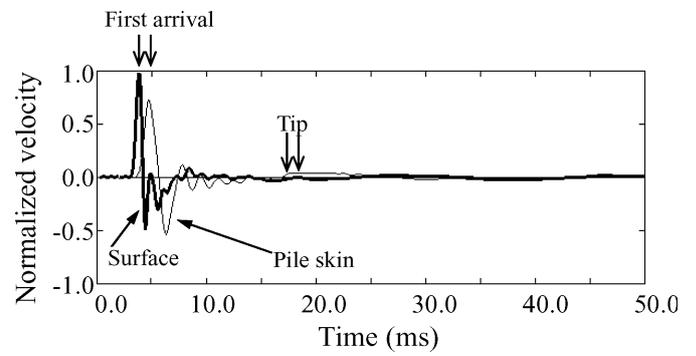


Figure 13. The responses measured on the surface and pile skin.

To examine the two-station measurement, an in-situ testing was conducted on one of slope protection piles. The pile is 15 m in length and 0.9 m in diameter. The long platform is 1.08 m in width and 0.38 m in thickness. The excavated foundation is 5 m in depth. The pile side which is faced to the deep foundation was seen intact. One accelerometer is mounted on the platform surface over the pile and the other is mounted on the skin 1.38 m below the surface. Two responses are compared in Fig. 13. The suspected reflections which arrive at the second receiver at time about 19 ms are also found in the response of the first receiver. The time interval is approximate to the first arrival interval. We can conclude that the reflection is from the pile tip according to the arrival time. The other reflections are excluded from the pile body since these time intervals are not approximate to the first arrival interval.

5 CONCLUSIONS

The waves in platform-pile systems are repeatedly reflected from the boundaries of the platform. Energy of the multiple reflections in the platform is controlled by thickness of the platform and relative cross-sections of the platform and the pile. The reflections from the tested pile body are obscured by those from the platform.

Effects of the reflections from the neighboring piles on the response over the tested pile must be taken into consideration for the integrity testing of piles in platform-pile systems.

The filtering technique, comparison of the responses and two-station measurement are suggested to exclude the multiple reflections in the platform and the reflections from the neighboring piles and identify the reflections from the pile body.

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