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Studies on parallel seismic testing for integrity of cemented soil columns*

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Abstract: The principle and process of parallel seismic (PS) testing for the integrity testing of cemented soil columns are introduced in this paper. A three-dimensional (3D) finite element model (FEM) for the pile-soil system is established for impulse responses. Under saturated soil or unsaturated soil condition, several vibrating velocity-time histories at different depths in parallel hole are obtained based on the numerical simulation. It shows that the length of the pile and the one-dimensional (1D) P-wave velocity in the pile can be determined easily from the features of the mentioned velocity-time histories. By examining the slopes of the first arrival time plotted versus depth or the depth where the amplitude of the first arrival significantly decreases, the length of the pile can be determined. The effects of the 3D P-wave propagation through the saturated soil and the defect of the cemented soil column on the velocity-time histories are also investigated.

Key words: Parallel seismic (PS) testing, Cemented soil columns, Integrity testing, Numerical simulation
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INTRODUCTION

Cemented soil columns are commonly used to strengthen soft clay foundations. In the last twenty years, engineering practice shows that it is difficult for the quality of the cemented soil columns to meet the required standard because of the variety of the soil property, construction techniques and managements which often leads to accidents. Therefore, it is very important to enhance the management of the quality and test integrity of the cemented soil columns for engineering safety.

At present, the common methods for testing the integrity of cemented soil columns include excavation tests (commonly used in the superficial part of the pile), portable sounding test, static loading tests of single pile, static loading test of composite foundation and core-drilling test. Furthermore, the construction log is supplementary for the judgment of the integrity. The excavation tests and static loading test only can identify the quality and engineering properties of the superficial part of the pile, and portable sounding test and core-drilling test only can identify the local engineering properties of cemented soil column. In order to obtain the complete properties information of the pile and enhance the rate of examination without additional expenses, engineers and researchers have introduced the low strain reflected wave test to test the integrity of the cemented soil columns in the last ten years. The low strain reflected wave test is effective in evaluating the integrity of the reinforced concrete pile. Whereas, the ratio of Young's modulus of the pile and the soil is low and the components of the cemented soil column are not uniform. The waves obtained by the low strain reflected wave test are complicated and difficult to distinguish from the reflected signal. It is difficult for low strain reflected wave test to obtain reliable results. Therefore, low strain reflected wave test is prohibited to be used to test the integrity of cemented soil columns by National Technical Specification in China.

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The testing of cemented soil column should take the property of the cemented soil columns and their convenience into account. The wave speed measuring methods of soil are commonly used in China. Down-hole method of shear wave testing (or the stratum longitudinal wave speed measuring method) of those methods involves striking ground surface and using a hydrophone to record waves at different depth. The wave velocity of the soil can be determined by the time-depth profile. When the plans of reinforced concrete pile for older structures are lost over the years, Parallel Seismic (PS) testing can successfully evaluate the depth of the pile (Davis, 1995; Davis *et al.*, 1997). However, the wave velocity in the cemented soil columns is associated closely with the amount of the cement. When the amount of the cement is less, the wave velocity in the cemented soil column may be less than that in the soil. In such cases, it is still uncertain how or whether the transmissive signal can be distinguished. Moreover, what changes of the signals will happen in the existence of defects in the column? Once these problems are solved, it would be of great value in science and application to popularize this new method.

PS method (Olson *et al.*, 1996) is a direct transmission method developed in France in the mid 1970's to evaluate the integrity of drilled shafts and piles under the existing structures (Davis and Hertlein, 1993). It involves striking any part of the exposed structure connecting with the foundation; a hydrophone or a geophone moves along a pipe parallel to the pile to record the seismic waves traveling down along the pile. The major advantage of this method is that it can be used even when the pile is capped. All one needs is access to an area which is close to and in rigid contact with the pile. In partially saturated soils, Olson *et al.*(1995) reported the practice of pouring loose sand to fill the void between the soil and the casing. The test (Finno and Osborn, 1997) was conducted to evaluate PS testing at the National Geotechnical Experimentation Site at Northwestern University. In this paper, we validated the PS method by using a 3D finite element model (FEM). Additionally, the PS method was used to evaluate the integrity of cemented soil columns including determining the length of cemented soil columns. The differences between received velocity-time histories under unsaturated and saturated soil conditions were also investigated.

PRINCIPLE OF THE PS METHOD

Introduction of the PS method

The equipment required for the PS test (Olson *et al.*, 1996) includes an impulse hammer, a hydrophone receiver (or geophone receiver), and a portable computer with appropriate analytical software. The photographs of the PS tests and its equipment (OEI, 2006) are given in Fig.1. The testing procedure is illustrated in Fig.2.

(a) (b)

Fig.1 The PS tests (a) and equipment (b)

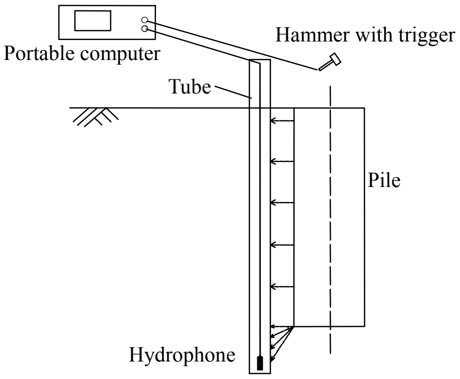


Fig.2 Specification for PS tests

To perform the test, a borehole adjacent to and slightly deeper than the pile must be drilled. Then, the pile head is struck with a hammer to generate stress wave energy, some of which travels down the pile and through the soil where the compression wave message is monitored by a hydrophone in an adjacent water-filled borehole. The transmission time of the stress wave between the point of impact and the receiver is measured. The hydrophone is initially located at the bottom of the borehole, and is raised by a short distance (A 0.5 m step is advised) after each hammer strike until the entire depth has been sensed. Transit times at different depths are measured and a profile of signals is built up, as shown in Fig.3. For a continuous pile in homogeneous soil, the first arrival time should increase linearly as the depth increases. As a defect is encountered, the travel time will increase accordingly, which indicates the depth of the defect. The same change will occur as the pile toe is encountered, thus providing a measurement of the length of the pile. Meanwhile, the bottom of the pile is defined as the depth where the amplitude of the first arrival decreases significantly.

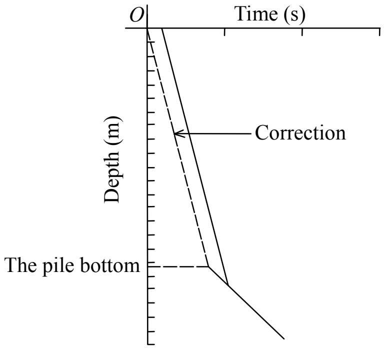


Fig.3 Idealized PS profile

For intact pile in uniform soil, the plot of the first arrival time versus depth appears as two straight lines at an angle. The inverse of the slope of the upper part corresponds to the P-wave velocity in the pile, and the lower part corresponds to the P-wave velocity of the soil located below the bottom of the pile. The change of slope takes place at the bottom of the pile, which can then be computed after a minor correction due to the distance between the pile and the probe. The upper slope is shifted through the origin, shown as a dotted line in Fig.3 and the lower part remains in its original position because of its propagation path.

Thus, it is easy to evaluate the integrity of the cemented soil columns by PS method. In addition, the PS method can provide the information about the soil below the pile toe.

3D FINITE ELEMENT ANALYSIS OF PS METHOD

3D finite element model

Eight-node, isoparametric finite elements are used to model the cemented soil column and the surrounding soil. The soil layer terminates on a rigid base. Boundaries are placed far enough to avoid any spurious stress wave reflection returning back to the zone of interest. The cemented soil column is usually short. Hence, the reflected wave from the boundary will arrive at the hydrophone later than that from the pile. So, the effect of the boundary reflection is avoided.

3D FEM models (Chow *et al*., 2003; Huang *et al*., 2006) were developed to simulate PS testing. As the strains of the cemented soil column and the soil are low, the cemented soil column and soil are assumed to behave linearly elastic and the material damping is assumed to be negligible. No relative displacements are allowed at the pile-soil interface. Fig.4 shows a 3D finite element scheme. The geometric shape and the element grids are determined on the basis of trial calculations. The criteria are:

(1) The stress and displacement distribution does not change appreciably with the expansion of the zone of interest.

(2) The size of the elements in the zones of high stress gradients should be as small as possible while the size of the elements around the boundary can be larger.

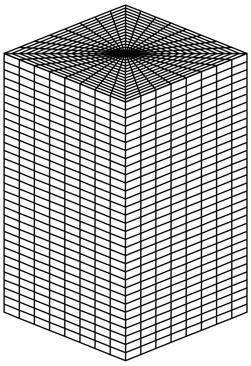


Fig.4 Finite element scheme

According to the criteria, the results of the trial calculations show that the bottom boundary should be set in depth of $3L_l$ from the head of pile (L_l is the length of the pile) and be treated as a fixed boundary, while the lateral surrounding boundary should be set $10B$ (B is the diameter of the pile) away from the pile edge. The lateral surrounding boundary is restrained horizontally but allowed to slide vertically, as shown in Fig.5.

In the analysis, the piles are made of cemented soil. To simplify the analysis, the pile is assumed relatively rigid with a diameter B=0.6 m and a length L_l=8 m. In the paper, these values are used unless otherwise specified. The shear wave velocity, the density and Poisson's ratios of the pile, defective part of the pile, and subsoil properties are listed in Table 1.

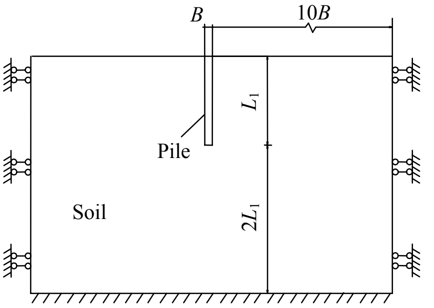


Fig.5 The schematic diagram of the FEM model

Table 1 Parameters used in the analysis

Material	Density (g/cm^3)	V_S (m/s)	Poisson's ratio
Pile	2.0	620	0.300
Defective section	1.8	426	0.350
Saturated soil	1.8	120	0.495
Unsaturated soil	1.7	130	0.350

A half-sine curve is used to simulate the pulse generated by the hammer impact at the center of the pile head. The width and the force peak of the pulse are 0.96 ms and 100 N respectively, as shown in Fig.6. The pipe is placed 0.5 m away from the edge of the pile. The global equations of motion are solved in the time domain by Wilson-θ's time integration scheme (Chopra, 2005; Küçükarslan, 2002). The simulation is implemented by the program ALGOR (an FEM program for finite method analysis developed by ALGOR Inc. of USA).

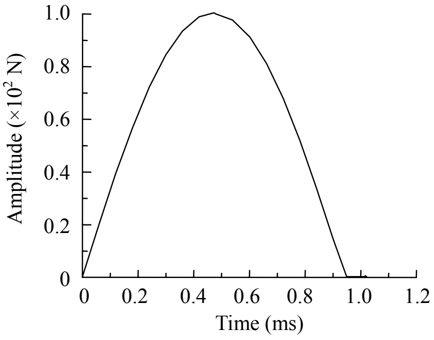


Fig.6 Half-sine curved pulse

Results of the simulation and the analysis

1. The propagation path in unsaturated soil and saturated soil

Under unsaturated soil conditions, the 1D compression wave velocity in the pile is greater than the 3D compression wave velocity in unsaturated soil and the first arrival is the 1D compression wave through the pile. The propagation path is shown in Fig.7. The propagation velocity and the length of cemented soil column can be easily determined.

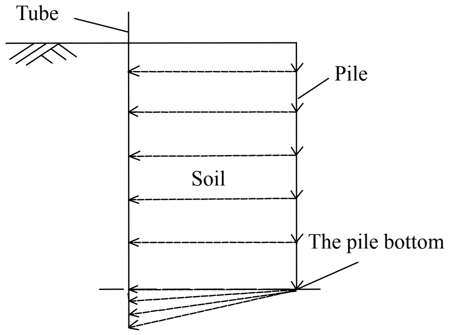


Fig.7 The propagation path under unsaturated soil condition

However, under saturated soil conditions, the 1D compression wave velocity in the pile is less than the 3D compression wave velocity in the saturated soil and the first arrival is the 3D compression wave through the soil. The propagation path is shown in Fig.8. The stress wave travels directly through the soil where the compression wave message is monitored by a hydrophone in the tube.

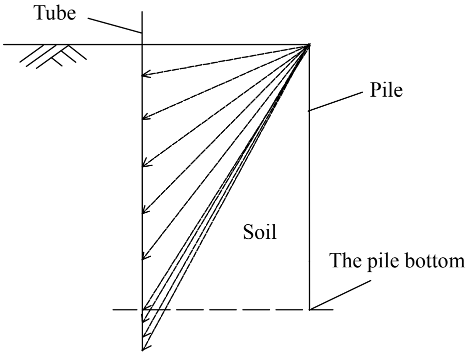
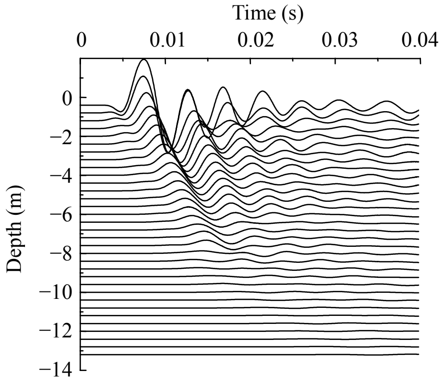


Fig.8 The propagation path under saturated soil condition

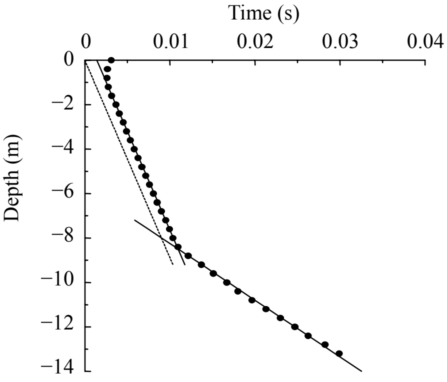
2. Simulating results of the intact pile

(1) Unsaturated soil condition

Simulating results for the PS test are shown in Fig.9. The waveforms at different depths are shown in Fig.9a. The first arrival (P wave) is distinct. The linear increase in arrival times versus depth can be easily distinguished. When the pile bottom is encountered, the amplitude of the first arrival significantly decreases. In Fig.9b, the length can be estimated to be 8.45 m by examining the position at which the change of the slope occurs (the error is 6.25%). After a slight modification as mentioned in Fig.3, the length is estimated to be 8 m, in reasonable agreement with the actual length of the pile. Meanwhile, by examining the magnitude of the first arrivals and selecting the bottom of the pile as the point where a significant reduction occurs in the amplitude of the first arrival, the length of the pile can be estimated to be 8 m, also in reasonable agreement with the actual length of the pile.



(a)



(b)

Fig.9 Simulating results of intact pile for unsaturated soil condition. (a) The calculated waveforms; (b) The calculated PS profile

The propagation velocity of the cemented soil (or pile material) can be estimated as the inverse of the slope of the first arrival time versus depth line. The inverse of the slopes of these lines represents the propagation velocities through the piles because for vertical piles and vertical access holes, the only increase in arrival times should be caused by longer travel times in the concrete. In Fig.9b, the inverse of the slope of the upper line resulted in a value of 1024 m/s which agrees reasonably well with the actual compression propagation velocity of 1000 m/s (V_P) through pile (the error is 2.4%). The value is slightly greater than the actual value because of the 3D effect near the pile head. Similarly, the inverse of the slope of the lower line resulted in a value of 254 m/s which agrees reasonably well with the actual compression wave velocity of 249 m/s (V_P) through unsaturated soil (the error is 2.0%).

(2) Saturated soil conditions

Simulating results under saturated soil condition of the PS tests are shown in Figs.10 and 11. The 3D compression wave velocity of 1250 m/s through saturated soil is greater than the 1D compression wave velocity of 1000 m/s through the pile. Hence, the waves propagating through the soil arrive firstly at the hydrophone. Thus, there are high frequency surges in the foreside of the signals because the signals are affected by the wave propagating through soil. Thus, the waves are complicated, as shown in Fig.10. Especially, due to the attenuation of wave amplitude and the effects of the overlap of compression and shear waves, the interpretation of the first arrival profiles of the lower portion of the waves becomes more difficult. As shown in Fig.11b, the first arrival of the lower part is more discrete. The length of the pile can be estimated to be about 8 m where a reduction occurs in the amplitude of the first arrival. This is also in reasonable agreement with the actual length of the pile.

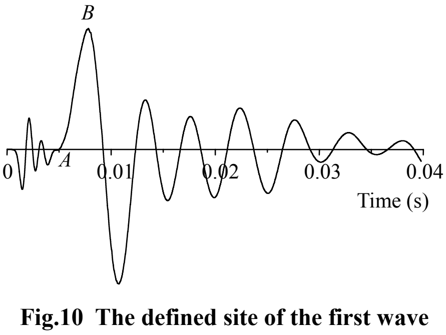
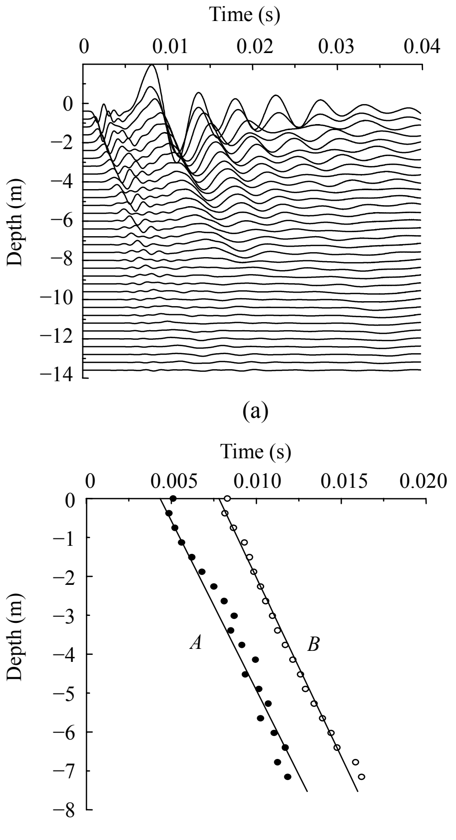


Fig.10 The defined site of the first wave

According to the time of the first arrival (A) and successive wave peak (B) propagating through pile, a compiled profile of signals for the various shots taken at different depths are shown in Fig.11b. The first arrival (A) propagating through pile is not easy to be distinguished because of the effect of the 3D compression wave propagating through soil. Therefore, the distribution of the shots is a little scattered in contrast with its corresponding fitting straight line. The amplitude of the succeeding wave is large enough to distinguish the wave peak (*B*) easily. The distribution of the shots corresponds reasonably well with its corresponding fitting straight line. The inverses of the slopes of lines *A* and *B* result in a value of 948 m/s (the error is 5.2%) and 961 m/s (the error is 3.9%) respectively. Obviously, the error determined by the wave peak is less than that determined by the first arrival under saturated soil conditions.



(a)

(b)

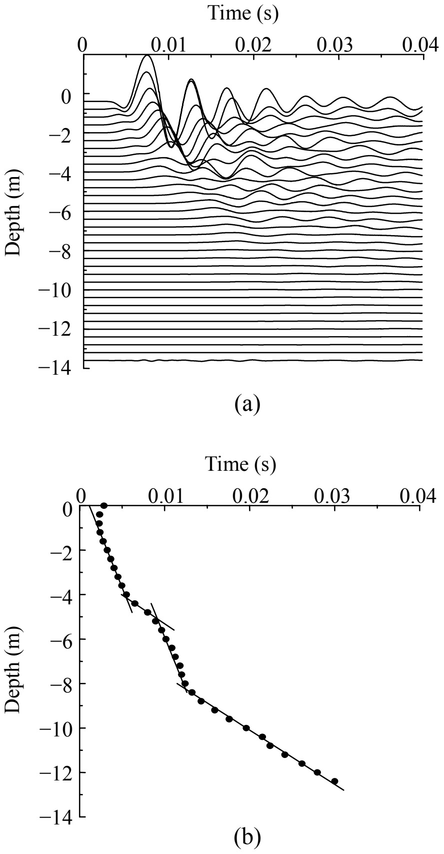
Fig.11 Simulating results of intact pile under saturated soil. (a) The calculated waveforms; (b) The calculated PS profile

3. Simulating results of a defective pile

The defect is set at the depth from 4 m to 5 m (the defect length is 1 m). The density, shear wave velocity and Poisson's ratio used for the defective part of the pile are 1.8 g/cm^3, 620 m/s and 0.35 respectively. The other parameters are as noted above.

(1) Unsaturated soil conditions

The wave is clearly visible and easy to identify the first arrival at the depth from 0 m and 4 m, as shown in Fig.12. Comparing Fig.9 with Fig.12, the differences between the signals obtained from the intact pile and the defective pile are obvious. In Fig.12a, significant reductions occur in the amplitude of the first arrival at the depths of 4 m and 8 m. The PS profile is shown in Fig.12b. The defect of the pile can be estimated at the depths from 4 m to 5.5 m and the length of the pile can be estimated to be 8 m by noting the changes in slopes of first arrival time vs depth. The inverse of the slope of the line from 0 m to 4 m is the same as it is from 5.5 m to 8 m. Therefore, materials from 0 m to 4 m and from 5.5 m to 8 m are uniform.



(a)

(b)

Fig.12 Simulating results of anomalous pile under unsaturated soil. (a) The calculated waveforms; (b) The calculated PS profile

(2) Saturated conditions

The wave propagation velocity in saturated soil is greater than that in unsaturated soil. So, the wave propagating through the pile is affected by the wave propagating through the saturated soil. As shown in Fig.13a, the waves are very complicated and it is difficult to distinguish the first arrival time. Moreover, the wave propagating through the pile is affected by the defective part and the wave propagating through the saturated soil. The compiled enlarged waveforms are shown in Fig.13b. One important feature of this plot is the attenuation of the signal at 4 m. When the depth is larger than 5 m, the amplitude is slightly higher than those above. The depth of the defect can be estimated to occur at 4 m by examining the change of amplitude. The length of the pile can be identified by using the same method, i.e., examining the magnitude of the first arrivals where they decrease significantly. The length of the pile can be estimated to be 8 m by using this method.

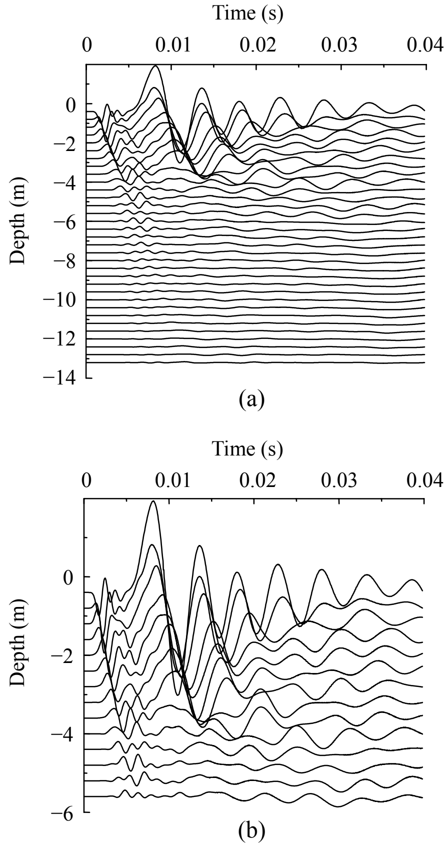


Fig.13 Simulating results of defective pile under saturated soil condition. (a) The calculated waveforms; (b) The compiled enlarged waveforms

CONCLUSION

In this paper, the PS method is validated on the basis of a 3D finite element model. Additionally, the PS method is used to evaluate the integrity instead of simply determining the length of cemented soil column. The differences of received velocity-time histories under unsaturated and saturated soils conditions were also investigated.

(1) By examining the slopes of the first arrival time plotted versus depth or by examining the depth where the amplitude of the first arrival decreases significantly, the length of the intact pile can be estimated.

(2) Under unsaturated soil conditions, 1D compression wave propagation velocity in the pile is greater than 3D wave propagation velocity in saturated soil. The pile is struck with a hammer to generate stress wave energy, some of which travels down along the pile and through the soil where the compression wave is monitored by a hydrophone in an adjacent hole. For a continuous shaft in homogeneous soil, the profile of the first arrival time versus depth is bilinear. The length of the pile is determined by the intersection. The wave velocities of the pile and the soil can also be determined by the slopes of the corresponding lines. Additionally, the local defect can be reflected in the signals.

(3) Under saturated soil conditions, when the 3D compression wave velocity through saturated soil is greater than 1D compression wave velocity through pile, the first arrival is the 3D compression wave. The wave propagating through pile is affected by the wave propagating through the saturated soil. The waves are very complicated and it is difficult to distinguish the first arrival time. Moreover, the waves are more complicated below the defective part. Thus, the defective part and the length of the pile could not be estimated exactly by examining the slopes of the plot of the first arrival time versus depth. But, the integrity and the length of the pile can be estimated by observing the succeeding wave peak and other appropriate parts of the waveforms except those of the first arrival wave.

(4) The PS method is a direct transmitting method, which can be easily performed and is intuitive. It is worthy to develop the theory and test of this method which should be improved.

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