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INTERPRETATION OF PILE INTEGRITY TEST RESULTS OBTAINED FROM MODEL CONCRETE PILES HAVING TWO DEFECT LOCATIONS

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ABSTRACT: The most common query for piles is that whether their integrity is acceptable. Another problem that has been rarely questioned is that whether a minor defect under a major defect is properly detected. This study constructed model concrete piles having the dimensions of 0.15 by 0.15 by 5.00 m with two defects intentionally created at 2.50 and 3.50 m from the pile top. The first defect was created to have a constant β value of 40%; while the second defect was varied such that the β values were from 95, 90, 85, 80, 65, 50, 35, and 20%. A pile integrity testing equipment was used to detect those defects; and the results were compared to the actual ones created. Testing was conducted on the piles being in the air and under the ground in order to observe whether skin friction would affect the signals. For the first defect, it was found that the average measured β values for both defects are about 76% and 89% higher than those of the actual ones. This is an important factor that engineers should bear in mind when interpreting the signals from a report. For instance, a defect reported is probably less than what has happened to the pile. In the case of the second defect, the results revealed that if a β value is 89% and higher, the pile should be acceptable. However, if it is lower than 89%, other types of pile integrity testing should be carried out to clarify the result.

Keywords: Pile integrity, Seismic test, Defect, Concrete pile

1. INTRODUCTION

A structure comprises several parts, including beams, columns, slabs, walls, and foundations. It can be said that the foundation is one of the most important parts of the structure. Geotechnical engineers should first attempt to make use of shallow foundations because they are much cheaper concerning overall construction cost. When foundation soil is unable to support superstructure loads; however, deep foundations are required. Note that the deep foundation comprises barrettes, caissons, walls, and piles. Nonetheless, the piles are one of the most popular deep foundations. This is because they require no advanced technologies and techniques for construction. In addition, it may be concluded that, after decades of research, study, and experiment, the formulae being utilized to estimate pile bearing capacities are fairly accurate and reliable.

Two types of piled foundations that have been widely used are driven- and bored- piles. The former is normally pre-cast; then, it is driven into the ground by a driving machine. These practices have caused so many problems concerning the integrity of the piles installed. For example, driving concrete piles into very soft clay could generate tensile stress in the piles causing them to crack. In the case of piles to be driven in the very hard soil, attempting to achieve the desired depth could also damage the pile due to excessive stress, as evident in Fig 1. If the damage is near the pile top, it would be easy to correct. In the case where the damage is located at a lower part that one cannot observe, problems arise. In the case of bored piles, extreme care must be taken, especially during drilling and concrete pouring. In most cases, water mixed with a stabilizer such as a bentonite or a polymer is needed. Its roles include: (1) provides resistance to lateral earth pressure, (2) creates a cake layer to prevent water flowing into a hole, and (3) circulates and cleans the dirt suspended in stabilized fluid. In addition, concrete is normally poured by means of submerged tremie pipes.

These construction practices lead to many potential problems with respect to the integrity of a bored pile. For example, Fig 2 (a) displays a hole has been drilled out of position resulting in the misalignment of a steel cage. In the case of the soil near the surface is soft, surcharges imposed very close on a newly constructed bored pile may result in a crack, as illustrated in Fig 2 (b). During concrete pouring, a supervisor must constantly calculate the tremie tip to ensure it has been all the time submerged in the concrete at least 2 m; otherwise, the concrete would be mixed with the stabilized fluid thereby causing the purity of concrete, as shown in Fig 2 (c). In a rare case, lateral earth pressure may be so high that a casing collapses, as shown in Fig 2 (d).

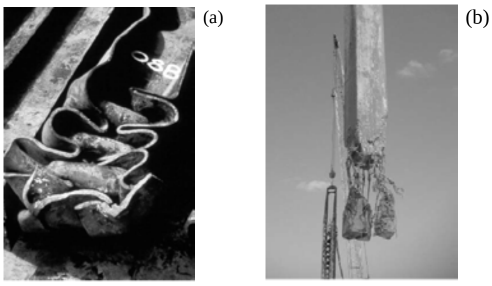


Fig.1 Damage to driven piles (a) H-section steel pile (b) precast concrete pile [1]

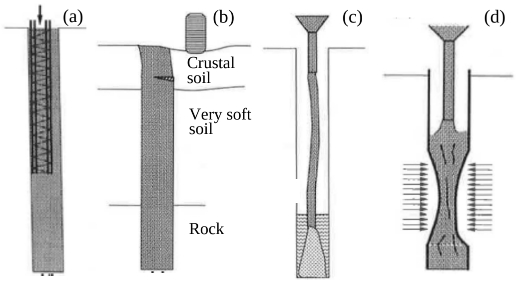


Fig.2 Examples of defected bored piles during construction (a) pile drilled out of position (b) no protection for fresh concrete, resulting in crack (c) concrete is poured through water (d) collapse of steel casing (adapt from [2])

Pile integrity testing methods have long been developed. Nowadays, they are the common practices for routinely checking the integrity of both driven- and bored piles. It is highly recommended that every single bored pile should be examined. For the driven pile, the frequency of testing depends on several factors. The details of methods, techniques, and result interpretations can be found in [3-5]. Even though being routinely employed, there have been rarely discussions concerning a pile having two locations of the defect, e.g., there are two defects at the locations of 5 m and 8 m from the pile top. This may be because when a first defect has already been detected, the second defect which is located at a lower part would be very difficult to properly identify, causing the disadvantage of the testing technique.

This paper provides the initial study with respect to attempting to interpret the pile integrity test results when there are two defects. It was achieved by first constructing model concrete piles having the dimensions of 0.15×0.15×5.00 m. After that, two defects were intentionally created at desired locations with different defecting levels. Next, a pile integrity testing machine was employed to conduct the integrity test. Then, the results were analyzed and compared to the actual levels of defect created, resulting in the interpretation of integrity testing of piles having two defects located at different depths.

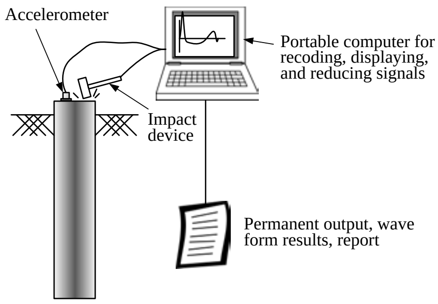


Fig.3 Typical test configurations for pile integrity testing (most tests do not measure the impact of a hammer)

2. PILE INTEGRITY TESTING METHODS

The pile integrity testing method has now been standardized by the American Society for Testing and Materials (ASTM). Since several methods and techniques have been being employed, the ASTM thus classifies the testing method into two types: (1) Pulse Echo Method, PEM, and (2) Transient Response Method, TRM [6]. Note that even though the methods officially classified, different terms are still being used around the world, depending on individual preferences. The former measures the pile head motion as a function of time while the latter measures both force and motion as a function of time. In addition, the TRM normally evaluates the signals by means of the frequency domain. Fig 3 illustrates how the integrity of a pile is determined. Typically, a pile integrity testing equipment comprises an accelerometer, plastic hammer, and portable computer. If the TRM is utilized, a hammer must be instrumented with a load cell or equivalent device. This study focused on the PEM method because it is so far the most used method in the industry.

Firstly, the pile top must be essentially cleaned and is at an approximately level. An accelerometer then is attached to the pile top via special wax or plasticine. A special-made nylon hammer provides an impact, generating the movement of the pile particles due to stress waves. The acceleration generated is picked up by the accelerometer attached to a computer. A program installed in the computer records, displays, and analyses the signals obtained, resulting in the wave velocity versus time (or pile length) for further analysis. Fig 4 shows a typical signal obtained from the PEM, including two wave reflections from defected location and pile toe.

To assess a PEM signal the wave velocity c of a pile material must be known; it can be calculated by the following equation

$$c = \sqrt{\frac{E}{\rho}} \tag{1}$$

where E is elastic modulus and ρ is mass density.

As the stress waves with a particle velocity v passing through a point the force F is generated; and, can be estimated from

$$F = Zv \tag{2}$$

where Z is pile impedance, Z = EA/c, A is cross-sectional area of the pile.

During the stress waves traveling downwards, if the downward force F_{Down} encounters changes in pile impedance, a reflected wave is generated. For instance, if impedance changes from Z_1 to Z_2 a reflected wave of magnitude F_{Up} is generated. Thus, the magnitudes of F_{Up} and F_{Down} are related to the change of impedance at a location; and, can be estimated from the following equation [7]

$$F_{\text{Up}} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right) F_{\text{Down}} \tag{3}$$

Normally the downward wave is a compression wave; thus, the upward wave is a tension wave if the wave travels from higher impedance to lower impedance, or $Z_2 < Z_1$, and vice versa. At this point, it should be emphasized herein that the PEM method simply identifies the change in pile impedance of which involves many quantities such as cross-sectional area, elastic modulus, and mass density of a pile. Another point should be noted is that the reflected waves can also be generated from soil resistance variation along the pile shaft. Nonetheless, such reflections normally are of a low frequency of which can be easily identified [7].

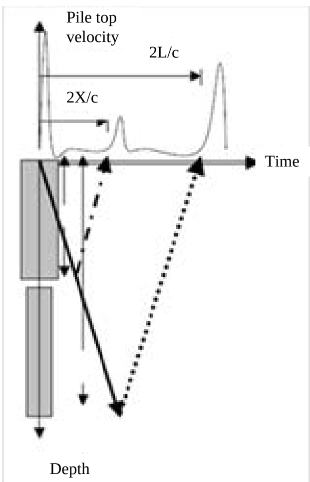


Fig.4 Schematic diagram showing the reflections from necking and pile toe [7]

The degree of impedance change has been quantified as a β value. For simplicity, it may be estimated from the relation Z_1/Z_2. Table 1 provides a guideline for assessing and reporting the results of the PEM test. Fig 5 and Fig 6 illustrate the signals for a normal- and defected- pile, respectively. It can be clearly seen that there is a reflected wave of tension at about 17 m from the pile top, indicating a change in impedance. In other words, this indicates a defect.

Table 1 Criteria for assessing the pile integrity [7]

$\beta = Z_1/Z_2$	Damage assessment
1.0	Uniform
0.8 - 1.0	Slight damage
0.6 - 0.8	Damage
< 0.6	Pile with a major discontinuity

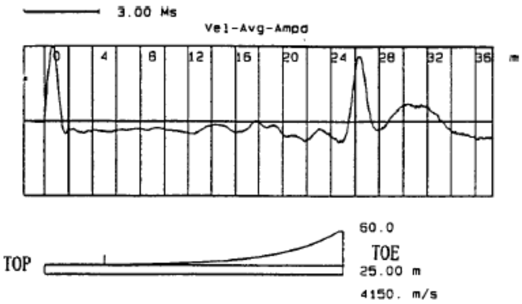


Fig.5 Typical velocity record for uniform piles [6]

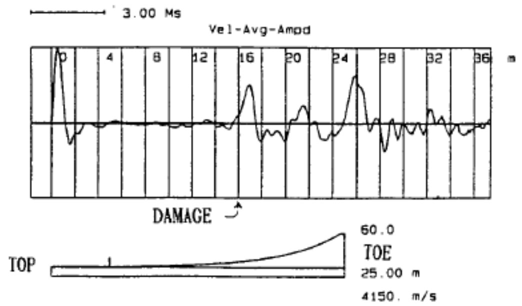


Fig.6 Example of velocity record for non-uniform pile [6]

3. MODEL PILES AND METHODS

3.1 Model concrete piles

To achieve the purpose of this research, model concrete piles having the cross section of 0.15 by 0.15 m and 5.00 m long were constructed, as shown in Fig 7. Two defects were intentionally created at 2.50 m and 3.50 m from the pile top. The former was by means of removing some pile material such that the cross-sectional area was left about 40% (60% extracted), as schematically detailed in Fig 7 (b and c). The latter defect located at 3.50 m from the pile top, however, was created by gradually extracting the pile material from 0, 5, 10, 15, 20, 35, 50, 65, and 80 %, resulting in the β values of 100, 95, 90, 85, 65, 50, 35, and 20%, respectively. Fig 8 displays the steps for creating those defects. Basically, a circular saw was first used to cut the pile to a specific depth. To obtain a desired cross-sectional area, the pile was essentially cut several times; then, an extractor was used to finalize the defect shape.

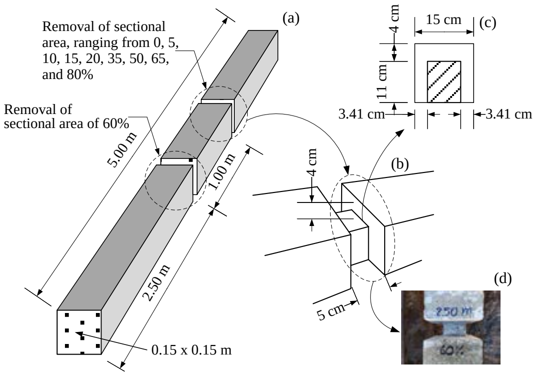


Fig.7 (a) Model concrete pile (b) and (c) details of defect at 2.5 m from pile top (d) actual defect at 2.5 m

Fig.8 (a) and (b) Cutting and marking a defect (c) finalizing the defect

3.2 Equipment

The pile integrity testing equipment used in this study was commercially obtained from PILETEST. The model was PET (Pile Echo Tester), which has been built according to ASTM D5882-07 [6]. Basically, it comprises a specially-made accelerometer with USB cable and a nylon hammer, as shown in Fig 9. The accelerometer has a sensitivity of 100 mV/V, the resonant frequency of 30 kHz, sampling solution of 24 bit, and sampling frequency of 50 kHz.

Plasticine was utilized for attaching the accelerometer to the pile top. A moderate force from the nylon hammer was generated at the pile top several times, resulting in stress waves traveling from the pile top and reflecting back when encountering an abnormality or pile toe. The signals were transmitted from the accelerometer via USB cable that was connected to a portable computer or tablet where a program for monitoring and recording the testing signals for further analysis was being installed.

3.3 Testing programmes and methods

The main objective of this study was to investigate whether a minor defect could be detectable even after a major defect was being detected. This is because it is quite possible for a pile to have more than one defect locations. This resulted in the two defect locations that were intentionally created as previously given in section 3.1. In addition, the defected piles were tested under two conditions: (1) in the air, and (2) 30 cm under the ground. Note that for both conditions the piles were horizontally laid for ease of testing. It should also be noted that this technique would not alter the test results. Fig 9 illustrates the testing technique carried out for the pile in the air and under the ground with respect to Fig 9 (a) and (b). Table 2 shows a number of tests being carried out.

Fig.9 Pile being tested in (a) the air (b) under the ground (c) a PC displaying the velocity record

Table 2 Details of the defects made for pile integrity test

No. of defect	Status of tested pile	Percentage of reduced sectional area		Symbols
		1st Defect[4]	2nd Defect[4]	
-	A[1]	-	-	ND-A
-	U[2]	-	-	ND-U
2	A	60	0, 5, 10, 15, 20, 35, 50, 65, and 80[3]	2-A0, 2-A5, 2-A10, 2-15, 2-A20, 2-35, 2-A50, 2-65, and 2-A80
2	U	60	0, 5, 10, 15, 20, 35, 50, 65, and 80[3]	2-U0, 2-U5, 2-U10, 2-15, 2-U20, 2-35, 2-U50, 2-65, and 2-U80

[1] : Pile was horizontally laid on the ground
[2] : Pile was horizontally laid 0.30 m under the ground
[3] : The defect was by means of gradually sectional area reduction from 0 to 80%
[4] :1st defect was constant at 60%; 2nd defect was by means of gradually sectional area reduction from 0 to 80%

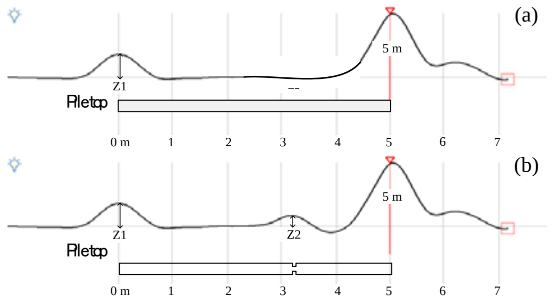


Fig.10 Examples of velocity record obtained from the machine employed (a) normal pile (b) defected pile

4. RESULTS AND DISCUSSION

A typical result obtained from the pile integrity test is simply a stress wave velocity versus pile length, as shown in Fig 10. The β concept has been adopted for assessing the integrity of a pile. For simplicity, it can be obtained by comparing the amplitude of a velocity record at a point Z_2 to the amplitude at the pile top Z_1. It should be noted that the pile top is assumed to have the β of 100%. In the case of bored piles, however, the amplitude at a point may be negative thereby resulting in a negative β. This means that the impedance at the point is higher than that of the pile top; in other words, there is probably bulging.

Fig 11 and Fig 12 display the velocity signals for the pile being tested in the air and under the ground, respectively. The figures show the velocity signal, pile top position, and actual and measured beta values. Tables 3 and 4 show the pile integrity test results with respect to the piles in the air and under the ground. They comprise test numbers, testing symbols, and percentage differences between the actual- and measured- beta values.

In the stress wave signals also show the β values, including $\beta_{A2.5}$, $\beta_{A3.5}$, $\beta_{M2.5}$, and $\beta_{M3.5}$ with respect to the actual β at 2.5 and 3.5 m, and the measured β at 2.5 and 3.5 m. It should be noted herein that the actual β values were intentionally created; while the measured β values were obtained from the pile integrity test machine.

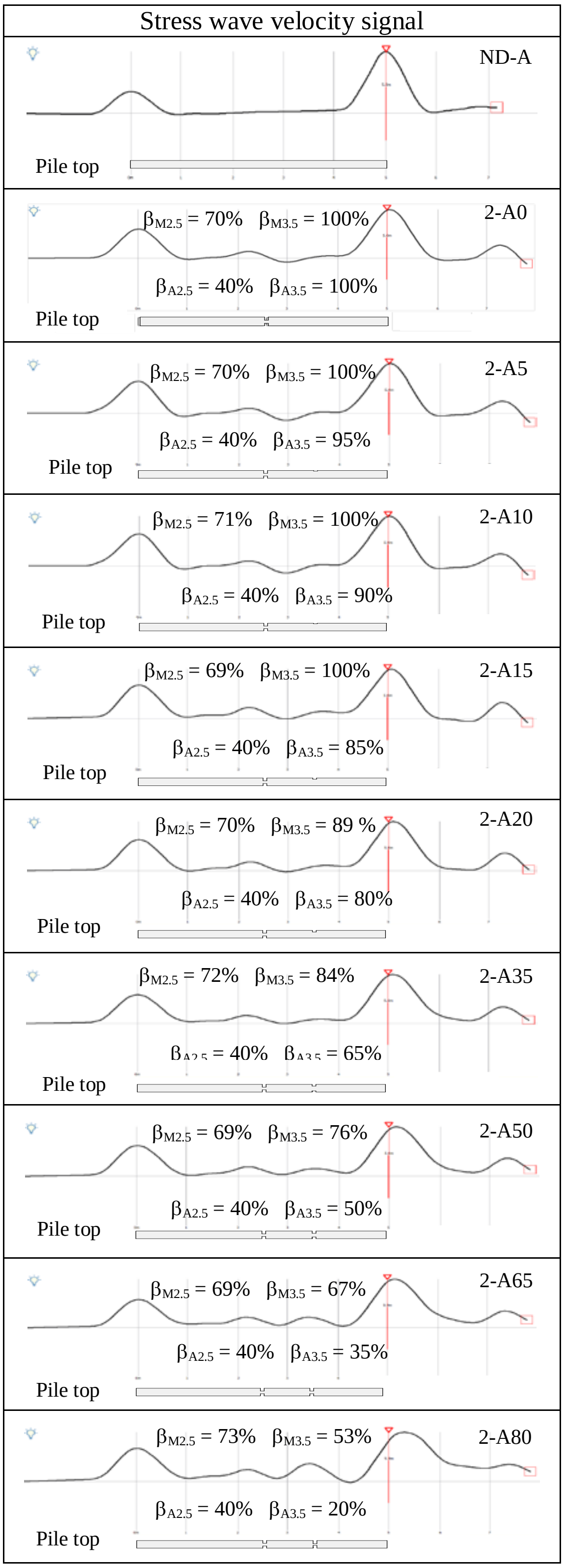
The ND-A and ND-U are the signals for the normal piles (no defect) tested in the air and under the ground, respectively. In the case of the ND-A, it can be seen that after the initial rise of the signal at the pile top the velocity is completely flat along the neutral line before rising up again at the pile toe. This indicates that the pile has no defect, i.e., no change of pile impedance along the pile shaft thereby having solid integrity. This behavior is quite similar to that of the ND-U, except that the flatline is slightly lower than the neutral axis. This probably was the result of the pile being buried underground; thus, the friction between the pile shaft and surrounding soil somewhat altered the traveling of stress waves.

To assess the detection of the second defect, all of the β values, including the actual and measured ones, are summarised and shown in the Tables 3 and 4. Consequently, all of the measured β values were compared to their actual counterparts in order to determine the differences between the actual and measured ones. This was very important to this research because the comparison would provide us the answer to our question, i.e., a second defect located lower a first major defect could be properly detected or not. Overall, for the pile in the air, it was found that the measured signals of $\beta_{M2.5}$ for all conditions are very similar, regardless of how the second defects created. This observation is also true for the pile being underground.

Moreover, it was found that the average $\beta_{M2.5}$ for the pile in the air was about 70%. Comparing this to the actual one of 40%, it can be said that the test results provide the β that is better than that of the actual one. In other words, the measured defect was lower than it actually was. This result was also observed for the pile under the ground, except that its average $\beta_{M2.5}$ was slightly higher at 76%. These results suggest that the friction along the pile shaft increases the β value. Thus, engineers should be careful when interpreting the pile integrity test results, i.e., bearing in mind that an actual defect may be more severe than what has been reported.

In the case of the second defect, the $\beta_{M3.5}$ values for the pile in the air were slightly greater than those of their actual counterparts $\beta_{A3.5}$ when the values are 80% or greater. However, when the $\beta_{A3.5}$ values were 65% or lower, the differences are exponentially increasing. For example, the $\beta_{M3.5}$ value for the 2-A80 was 53%, while the actual one was set at 20%, resulting in the difference of as much as 165%. These findings are also true for the case of the pile buried underground.

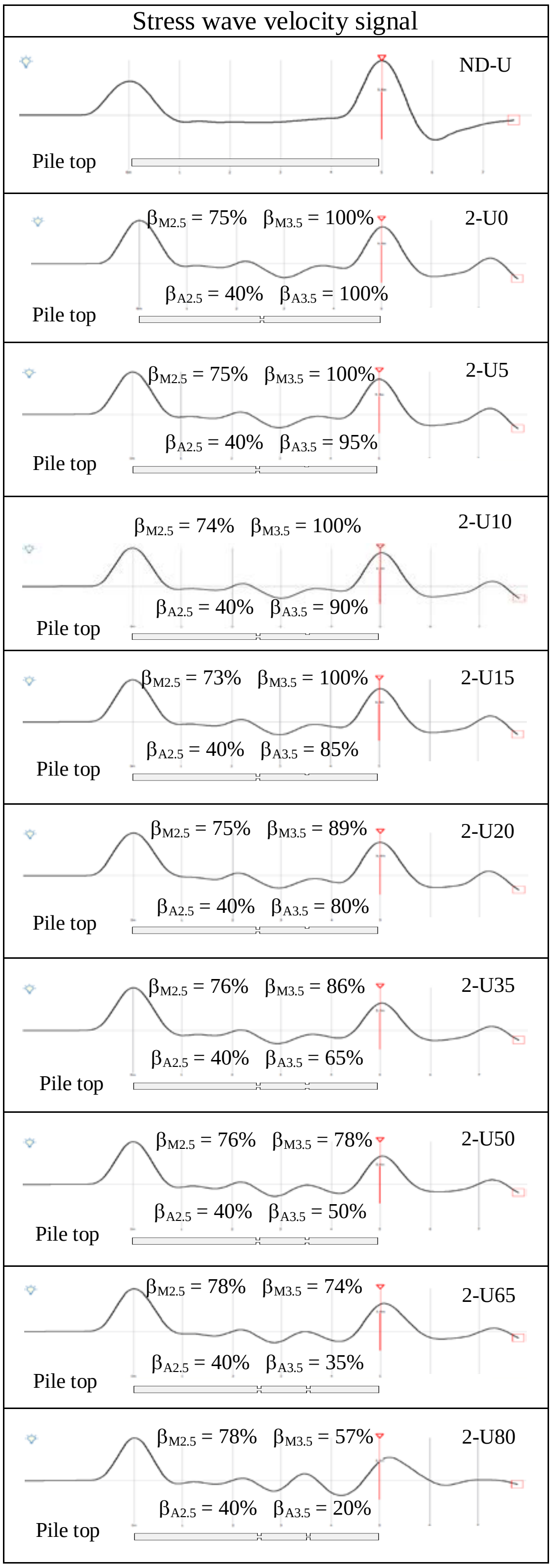
From these results and discussion, it may be concluded that a second defect located lower a major defect could be detected. To interpret the results, however, it shall be carried out with ultimate caution. For instance, if the measured β for a second defect is 90% or greater, engineers should not worry because the actual defect is about 80% and or greater. This is because, according to Table 1, the tested pile may be just slightly damaged. However, the final decision in terms of accepting or rejecting a pile must be based on several factors such as a type of project, single or grouped piles, and a pile type.



$\beta_{A2.5}$, $\beta_{A3.5}$ = actual beta values at 2.50 and 3.50 m.

$\beta_{M2.5}$, $\beta_{M3.5}$ = measured beta values at 2.50 and 3.50 m.

Fig.11 Pile integrity test results for pile in the air



$\beta_{A2.5}$, $\beta_{A3.5}$ = actual beta values at 2.50 and 3.50 m.

$\beta_{M2.5}$, $\beta_{M3.5}$ = measured beta values at 2.50 and 3.50 m.

Fig.12 Pile integrity test results for pile under the ground

Table 3 Result for the pile tested in the air

Actual β (%)		Measured β (%) Pile in the air			
$\beta_{A2.5}$	$\beta_{A3.5}$	$\beta_{M2.5}$	% Diff. to $\beta_{A2.5}$	$\beta_{M3.5}$	% Diff. to $\beta_{A3.5}$
40	95	70	75	100	5
40	90	71	78	100	11
40	85	69	73	100	18
40	80	70	75	89	11
40	65	72	80	84	29
40	50	69	73	76	52
40	35	69	73	67	91
40	20	73	83	53	165
Average		70	76		

Table 4 Result for the pile tested under the ground

Actual β (%)		Measured β (%) Pile under the ground			
$\beta_{A2.5}$	$\beta_{A3.5}$	$\beta_{M2.5}$	% Diff. to $\beta_{A2.5}$	$\beta_{M3.5}$	% Diff. to $\beta_{A3.5}$
40	95	75	88	100	5
40	90	74	85	100	11
40	85	73	83	100	18
40	80	75	88	89	11
40	65	76	90	86	32
40	50	76	90	78	56
40	35	78	95	74	111
40	20	78	95	57	185
Average		76	89		

5. CONCLUSION

Model concrete piles having the dimensions of 0.15 by 0.15 m and 5.00 m long were constructed having two defects located at 2.50 and 3.50 m from the pile top. The upper defect was created in order to have a β value of 40%. The lower defects were varied such that their β values are ranging from 95, 90, 85, 80, 65, 50, 35, and 20%. The pile integrity testing equipment model PET was employed to evaluate those defects. The integrity test was carried out under two conditions, pile horizontally laid in the air and 30 cm buried underground.

For the first defect, overall it was observed that the measured β values for the piles in the air and underground are about 76% and 89% higher than those of the actual ones. This means that one must be aware of the difference between a report and probably, the actual damage of a pile. In the case of the second defect, if the signals show that a β value is approximately 89% or greater, the pile may be acceptable. However, if a β value is lower than 89%, it should be ignored; and, other types of integrity test should be further carried out to clarify the integrity of the pile.

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