Quantitative Analysis of Low-strain Characteristics on Defective Piles with Constriction or Segregation

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Abstract: As one of the most commonly used dynamic pile test technologies, low-strain reflected wave method is increasingly used in pile integrity testing. Currently, field test is only operated in the simple discriminant of defect, but is lack of the comprehension of stress reflection law of different degree defects, especially of the quantitative analysis of defect. To solve the problem, differences between reflected wave of different defective piles are compared, situations with different segregation degrees are simulated with finite element method. The degree of pile concrete segregation was quantificational analyzed in accordance with the theory that velocity-time curve is consistent, which combines the defect characteristics of the ratio between reflected wave peak and incident wave peak ,and the concrete modulus between segregation section and the normal. The construction of finite element method will be significant guidance for practical engineering.

Keywords: Low strain dynamic testing, quantitative analysis of defect, segregation pile, the finite element.

INTRODUCTION

The principle of low strain test pile is to apply small exciting force on top of the pile to make longitudinal vibration stress wave propagate along the pile body, When it reaches a defect or the bottom of the pile, it generates reflection wave and transmission phenomena, finally by using speed sensor installed on the top of pile to receive the pattern of refection shape, thereby the existence of defects or the type of defects was judged. Necking and segregation are the most common defect types and they are harmful to the piles since piles are pulled too fast during pile formation, the mixture ratio of concrete is unsatisfied, and the effects of underground water etc. Current field test is used in the simple type identification of defect, but is lack of the quantitative analysis of stress reflection low of different degree defect.

1. Reflection Characteristic of Necking and Segregating Pile

Necking refers to, that some parts of the pile's diameter are less than the normal diameter. Segregation refers to that parts of pile's concrete modulus and density are less than that of other normal pile body. Necking and segregation are man-made during the pile foundation construction, and it is conceivable that either pile cross-section shock or high degree of segregation of pile concrete materials has a great effect on the capacity of pile [1].

When the elastic wave of exciting force incidents to the wave impedance interface, the relational express between the incident wave amplitude, reflected wave amplitude, transmission wave amplitude and wave impedance of materials is shown in formula (1).

$$a_1 = \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} a_1 \quad (1)$$

Where ρ is material density; c is the Wave propagation velocity in the medium; Z is the wave impedance. As shown in formula (2), the ratio of reflected wave amplitude $\hat{a}_1$ and the incident wave amplitude a_1 is called reflected coefficient.

$$\alpha = \frac{\hat{a}_1}{a_1} = \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} = \frac{Z_1 - Z_2}{Z_1 + Z_2} \quad (2)$$

As shown in formula(3), the ratio of transmission wave amplitude a_2 and the incident wave amplitude a_1 is called transmission coefficient.

$$\gamma = \frac{a_2}{a_1} = \frac{2\rho_1 c_1}{\rho_1 c_1 + \rho_2 c_2} = \frac{2Z_1}{Z_1 + Z_2} \quad (3)$$

Based on the defect characteristic, it can be learned that:

Necking pile: $\rho_1 = \rho_2$, $c_1 = c_2$, $A_1 > A_2$, α >0,the phase of reflected wave is equal to the incident wave.

Segregation pile: $\rho_1 > \rho_2$, $c_1 > c_2$, $A_1 = A_2$, α >0, the phase of reflected wave is equal to the incident wave.

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The theory analysis indicates that the characteristic reflected wave of necking pile and segregation pile are the same wave. While, there must exist some differences between the reflected wave of necking pile and segregation pile for their different formation mechanisms. By using finite element method, the difference is found out through a series of simulations shown as follows.

2. Wave Comparison Between Necking Pile and Segregation Pile

Tanchanis's research manifests that the model size with longitudinal length of 1.7 times of pile length and radial length of 24 times of diameter is large enough to the single pile analysis [2]. Randolph thought that the longitudinal length should be 2.5 times of pile length and the radial length should be 50 times of diameter [3]. The London clay test conducted by COOK indicates that the shear displacement can be omitted when soil diameter is 10 times of pile diameter and the soil diameter usually is 5-6 times of pile diameter in practical engineering [4]. Therefore, based on ABAQUS/Explicit, establishing the pile model, the pile length is set for 16m, the pile diameter is set for 1m, the longitudinal length of model is set for 24m, the model diameter is set for 10m, the necking radius is set for 0.25m, exciting force is set for 6N, and pulse width is set for 1ms. The element of pile and soil both are set for C3D8 [5]. On the premise of meeting the precision, the soil meshing size is 300mm while pile meshing size is 100mm, as shown in Fig. (**1**) and Fig. (**2**). The material parameters of pile and soil are shown in Table **1**.

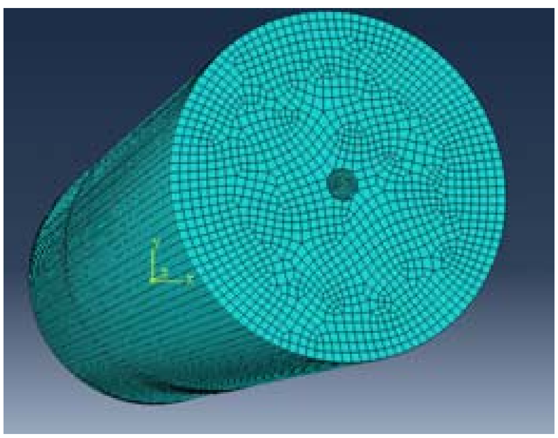

Fig. (1). model of necking pile-soil.

(1) As the diameter of pile □ the longitudinal wavelength, and the effect of transverse displacement to longitudinal vibration are omitted.

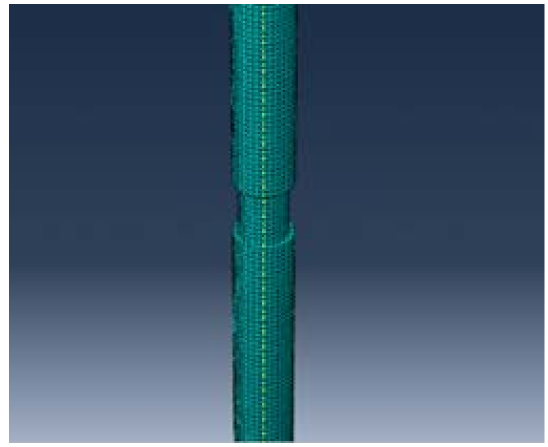

Fig. (2). model of necking pile.

(2) The soil boundary is set limitless in order to limit the model size and computational effort , which is not exist in reality. To avoid the fictitious reflected stress wave caused by model boundary, the soil diameter is set as 10 times as pile diameter and the outer layer is set as elastic semi-infinite unit. Because the exciting force is so small that element can absorb the stress wave propagating to the boundary effectively and eliminate the reflected stress wave caused by soil boundary [6]. Based on the speed formula of wave spreading in a medium: $c = \sqrt{E/\rho}$ and the pile-soil material parameter shown in Table **1** [7], it can be learned that the propagation speed of stress wave in pile is quite faster than that in soil (the speed in concrete is about 3194m/s～3800m/s, and the speed in soil is about 73m/s～230m/s). The computed time of post-process is set as 15～22ms in our study, only the velocity time history curve of wave is recorded during this period, which is reflected from pile bottom to the top, meanwhile the secondary reflection wave of soil around pile has not arrived yet. Thus the effect of the boundary secondary reflection to the final results is eliminated [8].

(3) In order to simplify the analysis, the concrete and rebar are set as linear elastic materials and the two can be regarded as a whole [9].

(4) The segregated part of pile is simulated by decreased material module in accordance with the practical conditions [10].

(5) The surface to surface contact is set as the contact between pile and soil. The contact between the bottom of pile and the soil is set as tie for convergence facilitating [11].

Table 1. Material parameter of pile-soil model

	Density	Elastic module	Potion ratio
Pile	2500kg/m^3	3×10^{10}pa	0.17
Soil around pile	1900kg/m^3	1×10^{7}pa	0.33
Soil under pile	2500kg/m^3	3×10^{9}pa	0.28

The defective piles are simulated with condition that the defect location from the pile top is 7.5m and both necking radium are 0.25m, the velocity time history curve of pile top with the defect length of 1m, 2 m and 3 m is respectively shown in Fig. (**3**).

(6) Meshing impacts the shape of reflected waveform. With the Mesh refinement, the main characteristics of velocity-time curve tend to stabilize. However, if the mesh is too small, the shape of reflected waveform at the bottom of pile will be attenuated. It's not good for waveform observation. In the premise of ensuring the accuracy and in order to improve the work effective, we set the size of mesh is 100mm.

The material parameter of segregation pile model [12]: elastic module $E = 1.5\times10^{10}$Pa ; density $\rho = 2100$kg/m^3 ; potion ratio ν=0.25. Under the condition of the defect located at the place from the pile top 7.5m, the velocity time history curve of pile top with the defect length of 1 m, 2 m and 3 m is respectively shown as Fig. (**4**).

The result indicates that the necking pile and segregation pile have the same basic characteristics of reflected wave, which is the same with the wave theory analysis. But there is a subtle difference between the two kinds of curves, ie, the curve of necking pile is mostly smooth while the burr can be found in the curve of segregation pile. The reason is that the stress wave will diffuse when the wave propagate to the segregated part which is inhomogeneous and of poor compactness. So the curve of segregation pile is similar with the curve of necking pile, but irregular.

With the necking length increasing to a certain extent, the positive and negative waves of defect reflected wave will separate and the characteristic reflection in bottom will obviously delay. With the segregated length increasing, when the segregated length is equal to 2 m, the positive and negative wave of defect reflected wave will separate obviously, while when the segregated length greatly increasing the positive and negative waves will not segregate. This is another significant distinction between necking pile and segregation pile.

3. Influence on Velocity Versus Time Curve Due to Pile Segregation and Quantitative Research

Segregation segment defect levels are determined by material properties of concrete, including modulus, density, etc [13]. In addition, the formula $c = \sqrt{E/\rho}$ also proves that modulus and density are important. In the following part, modulus and density parameter of concrete at the segregation segment are changed individually to analyze the influence on velocity versus time curve. The above mentioned finite element model of pile with segregation is still carried on; however, parameter of concrete at the segregation segment is changed to analyze.

This pile model has a 1m full-sectional segregation segment which distance over the pile top is 7.5m. Poisson's

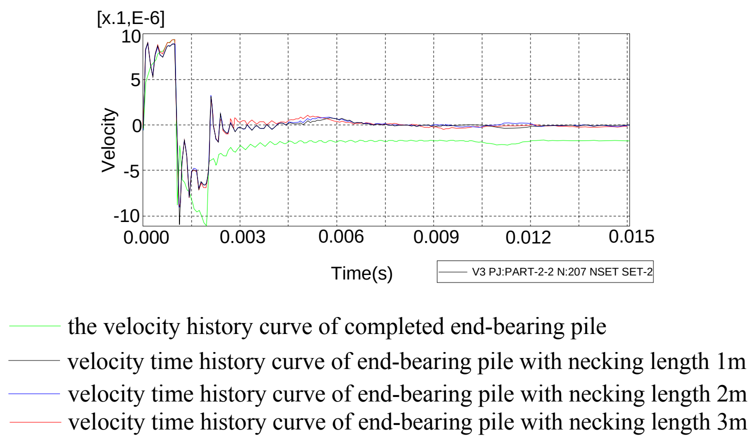

Fig. (3). velocity time history curve of end-bearing pile with necking length of 1 m, 2 m and 3 m.

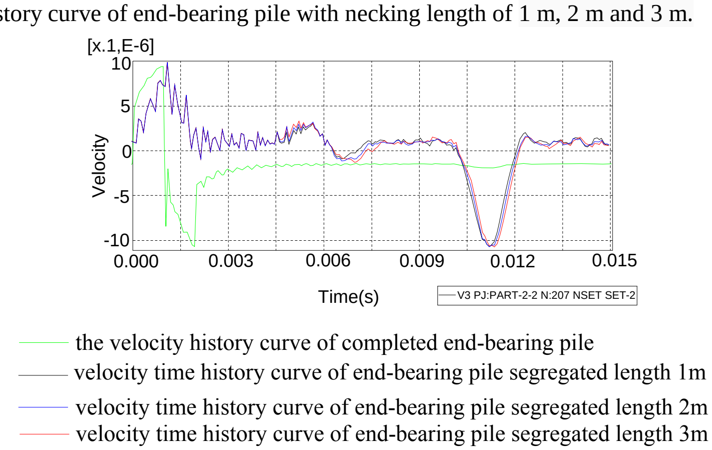

Fig. (4). velocity time history curve of end-bearing pile with segregated length of 1 m, 2 m and 3 m.

ratio is set to a value as 0.25. For segregation segment, elastic modulus is 1.5×10^{10}Pa , adjusted density to 2100kg/m^3 , 1000kg/m^3 , 210kg/m^3 get three velocity-time curves shown in Fig. (**5**).

As shown in the above figures, through ten times changes on density, incident peak and reflected wave peak of pile toe basically unchanged, influence on characteristic reflection amplitude of pile necking is not significant.

In this part, the pile model is similar to the above one with a 1m full-sectional segregation segment which distance over the pile top is 7.5m. Density value of segregation segment is set fixed as 2100kg/m^3, Poisson's ratio is set to a value as 0.25, adjusted modulus to 2×10^{10}N/m^2, 1.5×10^{10}N/m^2, 1×10^{10}N/m^2, 0.8×10^{10}N/m^2, 0.5×10^{10}N/m^2, 0.3×10^{10}N/m^2, 0.15×10^{10}N/m^2 get six velocity versus time curves shown in Fig. (**6**).

Parameters of the reflected waves at different modulus are shown in Table **2**.

As shown in Table **2**, characteristics of reflected wave peak increase gradually with magnitude reduction of modulus of the segregation segment, and pile reflection arrival delay occurs clearly. However, characteristics of reflected wave do not represent positive and negative pulses separation, and there is no change in the incident wave.

From the above figures demonstration, there is no influence on velocity versus time curve with an identical modulus and different density values. So, the modulus is concerned as the major factor affecting velocity versus time curve.

Extraction of the item ratio of segregation reflected wave peak to incident peak is shown in Table **2** to Table **3** which also include ratio of segregation segment concrete modulus to the normal.

Data obtained from Table **3** is used to carry out regression analysis which is shown in Fig. (**6**). In Fig. (**6**) [14], horizontal axis indicates ratio of segregation reflected wave peak to incident peak, vertical axis indicates ratio of segregation segment concrete modulus to the normal, in additional, R2 equals 0.9938. The curve with blue points is original loft curve and the black one without points is

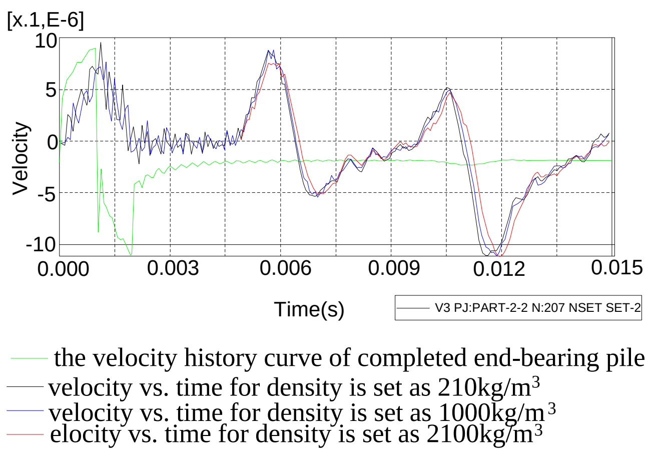

Fig. (5). velocity *vs*. time for density is set as 210 kg/m^3,1000 kg/m^3 and 2100 kg/m^3.

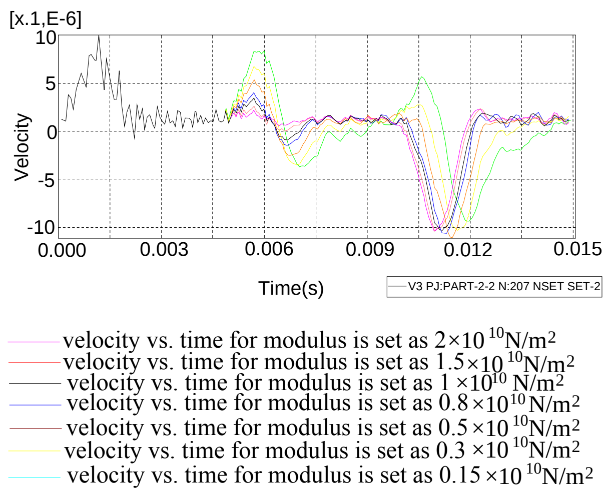

Fig. (6). velocity *vs*. time for modulus is set as 2×10^{10}N/m^2, 1.5×10^{10} N/m^2, 1×10^{10} N/m^2, 0.8×10^{10} N/m^2, 0.5×10^{10} N/m^2, 0.3×10^{10} N/m^2, 0.15×10^{10} N/m^2.

Table 2. Parameters of the reflected wave in different modulus

Modulus (N/m^2)	Incident peak(m/s)	Reflected wave of segregation(m/s)	Reflected wave of pile toe(m/s)	Time equation between defects peak and incident peak (m/s)	Time equation between pile toe peak and incident peak(m/s)	Ratio of segregation Reflected wave peak to incident peak	Ratio of reflected wave peak of pile toe to incident peak
2×10^{10}	1.33	0.14	1.78	4.78	9.87	0.105	1.33
1.5×10^{10}	1.33	0.2	1.76	4.79	9.87	0.15	1.32
1×10^{10}	1.33	0.33	1.78	4.81	10	0.24	1.33
0.8×10^{10}	1.32	0.42	1.77	4.83	10.04	0.31	1.34
0.5×10^{10}	1.33	0.63	1.85	4.87	10.21	0.47	1.39
0.3×10^{10}	1.33	0.83	1.70	4.91	10.52	0.62	1.28
0.15×10^{10}	1.33	1.06	1.56	4.95	11	0.8	1.17

Table 3. Ratio of weave peak and ratio of concrete

Ratio of segregation Reflected wave peak to incident peak	0.105	0.15	0.24	0.31	0.47	0.62	0.8
Ratio of segregation segment concrete modulus to the normal	0.784	0.588	0.392	0.313	0.196	0.117	0.058

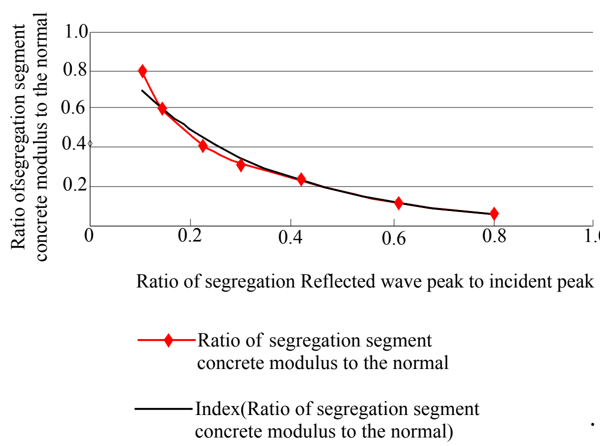

Fig. (7). ratio of weave peak.

regressive curve. The tracks of these two curves are similar. The trend line can be represented using formula (4) and proves that exponential function which better reflects curve variation is possible to determine the degree of segregation.

$$y = 1.0168e^{-3.5663x} \qquad (4)$$

4. CONCLUSION

(1) Ignoring soil resistance effects still satisfy the finite element calculations requirements.

(2) Compared with the integral pile, Incident wave phase of characteristic reflected wave of pile with necking or segregation is similar. However, the waveform of necking is smoother than segregation. Positive and negative pulses separation of defect waveform and pile reflection arrival delay will occur with the length increase of necking. Compared with necking pile, with the length and degree increase, segregation pile doesn't appear as similar situation such as positive and negative pluses separation which is an obvious distinctive characteristic for both the defective piles.

(3) Necking defect interface causes the falling of the wave impedance, so the reflected waveform is same to the incident waveform at the necking defect interface. The location variation of the necking is not effective on reflected waveform.

(4) Modulus of segregation segment of pile is an obvious major factor to impact the velocity versus time curve rather than density. And it can be concluded by formula (4).

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

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None decleared.

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