Acoustic Emission Monitoring of Sandy Ground under Sequential Pile Loading

Wuwei Mao, Shogo Aoyama, Shigeru Goto, Ikuo Towhata
Department of Civil Engineering, The University of Tokyo, Tokyo, Japan.
Phone: +81-3-5841-6123. Fax: +81-3-5841-8504; e-mail: maowuwei@geot.t.u-tokyo.ac.jp, aoyama@geot.t.u-tokyo.ac.jp, shigeru.goto@geot.t.u-tokyo.ac.jp, towhata.ikuo.ikuo@gmail.com

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1. Introduction

The behavior of subsoil subjected to pile loading is crucial for clarifying the pile bearing mechanism. Conventional investigations based on load-settlement analysis provide relatively few information on the subsoil behavior due to low sensitivity for representing of micro-scale stress-strain variations. In addition, it is commonly recognized that particle crushing becomes remarkable in highly stressed soils, and will eventually affect the mechanical behavior of the materials [1-3]. However, the significance of particle crushing has not been well recognized because of the difficulty in the identification of crushing occurrence during the process of loading. Generally, destructive excavations are conducted after tests, and the extent of crushing is quantified through comparison of the particle size distributions with original samples. In the current study, the acoustic emission testing method for monitoring of pile loading in sandy ground is presented. AE refers to the energy dissipation in the form of elastic waves from a stressed material [4], which accounts for partial of the total released energies. Therefore, it is possible to reveal the inner mechanical state of a material, such as the stress development or the impending failure, through AE monitoring. Different from the various active methodologies, such as ground-penetrating radar or ultrasonic testing, AE testing is a passive inspection technique and has been extensively used for nondestructive monitoring of various mechanical processes. The main objective of this study is to demonstrate the validity of AE monitoring techniques for evaluating displacement pile installation. In particular, the occurrence of sand crushing characterized by AE features are revealed and discussed.

2. Experimental Arrangements

A pile loading test was conducted in a rigid soil tank. The internal dimension of the tank was 600mm (length) × 600mm (width) × 500mm (depth). The closed-ended pile was cylinder-shaped with outer diameter of 40mm. A loading unit was installed on top of the frame with displacement control. Silica sand No.5 was used in this study, with Gs=2.651, D50 = 0.523mm, e\text{max} = 1.09 and e\text{min} = 0.66. The dry sand was prepared inside the tank layer by layer, and compacted to achieve relative density of 90%. The total height of the sand sample was 400mm. The penetration depth was 15mm for each sequential stage at a speed of 1mm/min. Unloading was conducted at the same rate before each new loading sequence.

The piezo-ceramic (PZT) type sensor was directly attached to the pile surface so that the excessive attenuation of elastic wave within sandy ground could be avoided. Here, the aluminum-made pile also functioned as a wave guide. The AE sensor (R-cast M304A) with integrated preamplifier was provided by Fuji Ceramics Corporation. The AE sensor (resonant frequency at 300 kHz) features a head amplifier incorporated within the sensor case immediately after the piezo-ceramic which improves sensitivity to low amplitude signals. At last, the AE signals were recorded by a high performance data logger (PXIe-6366, National Instruments Corporation) with a sampling interval of 0.5 μs throughout the test.
3. Results and Discussions

The emission of elastic waves from the sandy ground under pile loading may result from two main causes: sand sliding due to particle rotation or mutual displacement, and sand crushing due to particle breakage under high pressure. From single-particle fragmentation tests, Mao and Towhata [5] found that the crushing of individual particles are characterized by high frequency AEIs (>100 kHz). In contrast, the AE signal generated by frictional sliding is dominated by relatively low frequency components. The significant difference in the frequency content between these two types of events helped interpret the AE signals recorded during the pile loading tests. Fig.1 shows the evolutions of load-settlement and AE activity during the first two sequential loadings. Here, the curves with solid circles represent all detected AE events recorded during pile loading. It can be seen that the shape and tendency of the AE counting and load-settlement curves reveal high similarity. On the whole, the activity of AE can be divided into three stages: stage one (around the first 2mm of penetration), both counting number and the increment speed of the emissions were relatively low; stage two, the activity of AE increased rapidly to a high level; stage three, the AE events maintained at a high level and became relatively stable. This trend became more apparent during the re-loading tests, in comparison to the initial loading test.

![Fig.1 Comparison between the evolution of load-displacement and AE activity during (a) initial loading, (b) 2nd re-loading](image)

The curves with hollow circles in Fig.1 represent the AE events with dominant frequency content exceeding 100 kHz, which are interpreted to be events associated with sand crushing. It is seen that sand crushing generally occurred throughout the whole pile penetration processes. Similarly, a three stage AE evolution trend can be identified. This suggests that the extent of sand crushing is also closely related with the stress status of the ground. Fig.2 shows the ratio of sand crushing and sliding AE counting changing with pile penetration. All curves show that at the very beginning of each loading sequence, the ratio was low and then rose sharply with the process of pile penetration. This observation suggests that the sand crushing was not significant under low stress conditions. Conversely, it occurred substantially when stress was high. Another notable feature in Fig.2 is that during the first loading, it took more time to reach the reference line where the counting number of crushing and sliding is the same. All three re-loading sequences exhibited a significantly higher rate of reaching the reference line. Additional loading sequences took even less time, although to a less notable extent. This observation of hysteresis demonstrates the effect of previous loading history on the crushing behavior of the highly stressed sand. The significance of sand crushing was
evidenced by the grain size distribution tests conducted after the pile test, as shown in Fig.3. It is shown that the fine content of the sand increased greatly after pile penetration, while the amount of the large size particles (>0.42mm) decreased, providing a direct evidence of sand crushing.

4. Conclusions

This study presents an acoustic emission-based methodology for monitoring of a single pile under sequential loadings in sand. In general, three stages of emission rate evolution can be identified with cumulated ground resistance: a low emission stage, a rapid increase stage, and a stable stage. The evolution tendency of AE revealed high similarity with the load-settlement curve. In addition, AE events (higher frequency AEs) corresponded to sand particle crushing offers a new insight to evaluate the feature of sand grain crushing. The results obtained in this paper are beneficial for further clarifying the bearing mechanism of pile foundations

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