# 論文の内容の要旨
# Thesis Summary

論文題目　Experimental study on acoustic emissions during pile penetration in sand
（砂地盤への杭貫入に伴う AE 特性に関する模型実験）

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Pile foundation plays an important role in the modern infrastructure constructions. In pile foundation design, the bearing capacity of the pile shaft or pile groups is one of the key governing parameters. An accurate estimation of pile bearing capacity requires a profound understanding of the underlying mechanisms governing the behavior of piles in sand. However, conventional investigations based on load-settlement analysis provide relatively few information on the pile bearing mechanism due to low sensitivity for representing of micro-scale stress-strain variations of stressed sands. In addition, previous pile studies have revealed the importance of particle crushing in evolution of pile tip resistance. It is also difficult to use traditional methods to evaluate the onset and extent of crushing. Therefore, there is an ongoing demand for a better understanding of the subsoil behavior subjected to pile loading.

This study introduces a new technique to investigate the behavior of stressed soils by means of Acoustic Emission (AE). AE refers to the energy dissipations in form of elastic waves from a stressed material, which accounts for partial or the total released energies. In case of pile installation, the sands immediately below the pile tip and around the pile shaft are stressed and the energy is dissipated due to particle sliding or crushing in the form of elastic waves. Information carried within these AE signals is supposed to provide direct insights to the subsoil response during pile penetration. Therefore, this research is aimed towards developing the fundamental understanding of AE in stressed soils with reference to pile loading conditions. The basic experimental design and the main results are summarized as follows:

Firstly, the AE testing method was applied to monitor the processes of sand crushing and sand sliding, which are expected to be the two main sources of AE events from a pile penetration test. For sand crushing tests, the sand particle was placed between two metal plates and crushed by static loading using a serve-controlled motor. It was found that the high frequency AEs were mostly observed at high stress level, particularly when there was obvious decrease in bearing load. A clustering of AE signals with high frequency was observed when there was notable fluctuation of the bearing load. For sand sliding tests, three types of tests were designed to reproduce the process of sand sliding: two particle sliding controlled by hand, ruler moving in sand and hand stirring in sand. Most of the events obtained from the sand sliding tests have the

dominant frequencies less than 100 kHz, with very few exceptions. Previous studies from experiments with rock, concrete and sandstone samples confirmed that the AE spectra from fracture mechanisms is associated with high frequency AE. Therefore, it is argued that the high frequency components of AE (say >100 kHz) can be regarded as a hallmark of the ongoing fracturing. In addition, it is also found that different particle types (silica sand grain or coral sand grain) shared similar tendency of AE activity evolution and dominant frequency distribution, despite the difference in the absolute emission magnitude. This feature meets the practical demand for an easy and effective monitoring approach on the sand crushing problems.

Secondly, experiments were carried out in a pile loading system equipped with AE instrumentation. Two types of sands, silica sand and coral sand, were used as the testing materials. Three series of pile loading tests were conducted to explore the effects of sand type and loading procedurals on AE behavior. In the first series of tests, three types of silica sand samples with different relative densities corresponding to loose, medium and dense ground conditions were prepared. The pile was loaded once to reach a penetration depth of 100mm. In order to explore the effect of previous loading steps on the latter steps, another series of tests with silica sand were subsequently conducted. In this series of tests, the pile was loaded at every 20mm, and unloading was conducted before the next loading step. Totally five loading-unloading cycles were performed. In the third series of tests, coral sand with three different relative densities were tested. This series of tests aimed to explore the AE behavior in more crushable materials.

Based on AE testing results, it is found that the process of pile penetration was highly distinguished by AE activities. In generally, dense ground was more emissive than loose ground. And silica sand was more emissive than coral sand. The evolution tendency in terms of the AE count, AE amplitude and AE energy showed high similarity with load-settlement curves. During the unloading processes, the AE activity decreased rapidly after the initiation of unloading. In addition, the test results showed that the yield settlements obtained from both load and AE data were close. Considering that the yielding of the soil is closely related to the release of irrecoverable energy, therefore, the use of AE energy measurement for yielding determination seems reasonable. This suggests a new method of studying the yielding of soil other than the traditional stress-strain-based method. Moreover, the high consistency between AE and bearing load behavior make it possible to substitute one for the other under certain circumstances, e.g. AE monitoring during displacement pile installation.

In addition, significant difference revealed in the frequency domain of AE signals was used for distinguishing of sand crushing and sand sliding events. It is found that sand crushing occurred throughout the pile penetration process and became significant after the ground yielding. The ground is characterized by shear deformation along the shear zone after yielding. Therefore, the continuation of high-frequency AE events indicated a continuous high level of sand crushing, which is in accordance with previous studies that sand particles are more prone to crushing under shear than compression. In view of sequential loading, it may be generally stated that the overall density of the subsoil was gradually increased. The ratio of sand crushing and sliding AE counting 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, and occurred substantially when stress was high. This demonstrates that dense ground was subjected to more crushing, which is also evidenced by grain size distribution analysis.

Thirdly, the AE source location were performed to reveal the special positions of the AE events. An eight AE sensor array was set to surround the pile tip, and the locations of the AE events were computed based on their arrival times to the sensors. This includes the development of an automatic signal arrival time determination method based on Autoregressive/Akaike Information Criteria (AR-AIC) model, and an AE source location algorithm based on time of difference of arrival (TDOA).

Based on AE source localization, it is found that AE sources were not uniformly distributed below the pile tip, but concentrated within a region about 0.5~1D below pile tip. In general, the distribution of events was in form of radially extended manner, with the distribution density reduced outwards, indicating that the soils within this region underwent severest dislocation or crushing. AE distribution in dense ground was more concentrated, while in loose ground was more scattered. For dense case, the number of localized events at the beginning of loading was much less compared with that in the latter periods. It grew with the penetration and became relatively constant. By contrast, the loose case showed a continuous increasing trend as the penetration proceeded. Such a feature is similar with the AE activity evolution in forms of count, amplitude and energy, where loose case also exhibited more evident increasing trend after ground yielding. In addition, AE sources in coral sand were distributed within a more limited region, suggesting a higher level of stress concentration.

Microscopic observation of subsoil below pile tip after tests showed that the sand crushing mostly occurred in the shear zone. For sand immediately below the pile tip, there was a circular crushing zone around the pile edge, inside which no obvious crushing can be noticed. The non-crushing region shrank as the excavation advanced deeper and finally disappeared. The lower limit of sand crushing zone located approximately 1D below the pile tip. This is consistent with AE source concentration results. Therefore, the zone of crushing below a pile tip is roughly divided into four zones: the outer transition zone from the far side of pile tip, the shear zone, the inner transition zone and the compression zone immediately below pile tip. The sand in the shear band underwent severest crushing and is supplied with fresh sand from the frontal of fresh sand stream. The continuous fresh sand flowed into the shear band resulting in substantial crushing with the advancing of pile penetration, and consequently generated considerable AE. The sands localized around the center of the bottom shear zone would change the direction of flow most sharply when entering the shear band. This region is expected to be most “noisy” in terms of AE, which is consistent with AE source distributions. This is also evidenced by the PIV observations. The sands below the pile tip were “pushed” to the two sides of the pile. While for sands immediately below the pile tip, the horizontal displacement is insignificant. It should also be noted that the compression zone immediately below the pile tip may also subjected to severe crushing when the stress level is high enough. However, since shear failure is more likely to happen in case of pile foundation, it is more important to concern sand crushing within the shear band.

Finally, the AE monitoring method was applied to the group pile testing. The main objectives were to investigate the effect of pile spacing and individual loading on the AE characteristics among piles. Two different pile spacing, 2.5D and 5D, were tested. It is found that the center pile in case of 2.5D group pile showed much higher level of AE activity compared with the corner and middle pile. While in case of 5D group pile, the center pile showed no obvious difference compared with the other piles. This suggests greater interactions between piles in case of narrower pile spacing. The effect of individual loading on the group pile behaviors was evident in view of secant modulus for 2.5D group pile. Center pile exhibited higher value of secant modulus after group loading. Such feature disappeared after the disturbance of individual loading, and reappeared after subsequent group loading. However, in view of AE, the effect of individual loading is not well revealed, always higher AE observed in center pile. For 5D group pile, the variation of secant modulus was less significant in view of both load-settlement and AE behaviors, and center pile showed no notable difference of AE activity. It seems that AE may not be quite effective when it is discussed in the exact values. Rather, it is more useful to reveal certain transition point (e.g. ground yielding) where significant changes of AE activity can be identified.

The AE features revealed herein provide new insights into the energy dissipation of subsoil subjected to pile load. The features of energy dissipation is closely related with the ground bearing capacity development. The characteristics of subsoil behaviors revealed in the current study including extent of crushing as well as the location of crushing can be further utilized to modify the traditionally developed pile bearing theories, e.g. the cavity expansion theory, to achieve a better prediction of the pile bearing capacity. Potential application of the technique to field pile monitoring is promising as well.