Acoustic Emission Behavior of Tropical Residual Soil

Lim Jun Xian, Chong Siaw Yah, Yasuo Tanaka, Ong Ying Hui

Acoustic emission technique has extensively been used for a wide variety of engineering materials, but less attention has yet been paid on the application of this non-destructive technique to investigate the fundamental behaviors of geomaterial. In the present study, acoustic emission method was adopted in conjunction with the conventional stress-strain-time measurement to investigate the mechanical behaviors of a selected tropical residual soil. A systematic acoustic emission instrumentation setup, which was devised in a monotonic triaxial shear apparatus, was evidenced to provide reasonable experimental results. From the isotropic consolidation results, it was realized that the Kaiser's effect was observable and the pre-stressed level as induced by compaction could be determined through acoustic emission. In undrained shearing, the acoustic emission response was found to be corresponding with the axial strain measurement. Initial soil yielding, which was mobilized at small strain range, was also able to be determined. The acoustic emission response of the studied tropical residual soil also showed good similarity with the reported soils constituting considerable fines content.

***Keywords* : *Acoustic Emission, Tropical Residual Soil, Triaxial Shear Test, Isotropic Consolidation, Undrained Compression*.**

I. INTRODUCTION

All measurable soil responses are closely related to the particle-to-particle interaction within a soil matrix. This involves some micro-scale phenomenon, such as particle slippage or dislocation, grain crushing, particle fragmentation, and particle reorientation/ movement accompanying by global soil deformation [1] - [3]. It is no doubt that the micro-scale interaction of soil grains can very much influence the macroscopic observation and measurement [4]. When a soil specimen was compressed, strain energy will be accumulated and mobilization of soil grains within the soil matrix can be expected until a localized zone of stress-concentration is triggered to dissipate the accumulated energy. The irreversible energy can be dissipated in the form of heat, sound, or vibration, which has been proved to be measurable for the laboratory study of soil. To study the microscopic behaviors of soil, stress wave propagation, microscopic imaging, or sometimes local deformation measurements have been attempted [6] – [8].

To date, acoustic emission (AE) technique has been successfully applied on a wide variety of engineering materials, such as metal, concrete, rock, ceramic, epoxy composite, and even sandy soil [9] – [12]. Lockner [9] discussed the application of AE technique on a variety of rock in which sudden release of acoustic stress waves could be recorded, accompanying by numerous micro-cracks. With the adoption of several AE transducers, the source of emitted energy was able to be traced accordingly. As the AE response was governed by the pre-stress condition of a particular engineering material, the stress history, inherent fabric or structures, uniformity, and anisotropy are undoubtedly entailed. Koerner et al. [13] investigated the AE response of granular soil and cohesive soil through triaxial shear testing. It was reported that the acoustic emission response was inter-related with the deformation of soil. Further, Koerner et al. [14] correlated the typical stress-deformation behavior of clay, clayey silt, and sand with the obtained acoustic emission responses. In Japan, Tanimoto and Tanaka [12] carried out a comprehensive AE experimental study on the decomposed granite sandy soil. It was evident that Kaiser's effect could be proved and the elasto-plastic behavior could be distinguished by the acoustic emissions after irreversible soil mobilization had been initiated. On the other hand, Lord and Koerner [11] explored the AE technique to the field application for monitoring slope, dam, and embankment stability. Advance in field monitoring was accomplished by incorporating the AE measuring system into the pressure-meter instrumentation. Recently, Mao et al. [2] utilized AE technique for examining the crushing mechanism of silica sand particles during the pile penetration into the ground. It was found that individual particle crushing was characterized with a much higher frequency (>100 kHz) than the particle sliding (<100 kHz). The application of AE was also proved to be successful when comparing to the load-settlement curve of a penetrated pile. The finding was later underpinned by Lin et al [3] where a series of drained triaxial shear test on silica sand was examined through AE. It can be realized from the above review that the AE study has been intensively accomplished for coarse-grained material, but limited study has yet been focused on the soil composting of fines (silt and clay) which can be found in many natural soils.

Revised Manuscript Received on January 15, 2020

* Correspondence Author

Lim Jun Xian, Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, 43000 Kajang Selangor, Malaysia. Email: limjx3@1utar.my

Chong Siaw Yah*, Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, 43000 Kajang Selangor, Malaysia. Email: chongsiawy@utar.edu.my.

Yasuo Tanaka, Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, 43000 Kajang Selangor, Malaysia. Email: yasuo@utar.edu.my.

Ong Ying Hui, Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, 43000 Kajang Selangor, Malaysia. Email: ongyingh@utar.edu.my.

Although the triaxial apparatus being instrumented with AE measurement has been commercially available, it was well believed that a comprehensive methodology with regard to the AE instrumentation as well as signal processing could encourage and facilitate the researchers to carry out AE-related investigation on geomaterial at the most practical way.

Triaxial shear test is by far the most common experimental method to investigate the stiffness and strength behaviours of geomaterial. In a standard traixial test, the mechanical soil response was typically represented by the stress-strain measurement, pore-water pressure and volume change responses, depending upon the testing condition. At a very small-strain range (<10^{-3} %), the deformation of soil was required to be measured by using a more sensitive and sophisticated instrumentation. Bender element instrumentation can also be used to measure the shear wave velocity and soil anisotropy through the artificial propagation of polarized shear wave. Another special instrumentation to measure the soil deformation includes linear deformation transducer (LDT), through which localized axial strain of soil below 10^{-4} to 1 % could be measured accurately [15]. As the soil was sheared or compressed towards greater strain amplitude, external displacement was measured by a linear variable deformation transformer (LVDT). By combining the measured responses at small and large strain, kinematic yielding behaviors of soil could be formed for interpretation [7]. However, the measurement of soil deformation could become non-uniform and misleading once the soil specimen was sheared beyond 15 % of strain amplitude [16]. Uncertainties in measurement could sometimes be arisen due to setting-up disturbance and separate deformation measurements were carried out during the test. It was also evidenced from the fact that external strain measurement could provide under-estimation towards the experimental result [7]. In view of this, the AE method may be promoted as an alternative to trace the intrinsic change of soil state continuously in the experiment without disturbing the soil unfavorably as well as monitoring the internal energy dissipation under high sampling rate condition.

From the above critical review, it could be inferred that AE technique can be regarded as an alternative to investigate the progressive soil mobilization and kinematic yielding. Besides, most of the AE studies have only been focused upon clean sand and clay, whereas little attention has yet been paid on the AE behavior of soils constituting certain amount of fines content such as residual soil. In hot and humid countries, such as Malaysia and Singapore, there are numerous geotechnical structures relied on the natural ground made of tropical residual soil. It follows that advanced laboratory investigation is always welcomed to furnish valuable insights into mechanical behaviors as well as micro-scale interaction for tropical residual soil.

In the present study, mechanical behaviors of a tropical residual soil were investigated by using a developed triaxial apparatus instrumented with AE measurement. Supplementary attention was also given to the systematic development of an AE instrumentation setup for soil testing in the authors' laboratory as well as the methodology of signal processing for the obtained AE data.

II. MATERIAL AND METHODS

This section provides a detailed coverage for the development of a monotonic triaxial testing system being incorporated with the acoustic emission measurement. Design considerations and details for the base pedestal to accommodate the AE transducer were elaborated. Besides, data acquisition system for the real-time recording and monitoring of AE signal was included.

A. Tropical Residual Soil

A tropical residual soil from Peninsular Malaysia was selected for the present AE research. The weathering product was evolved from granitic rock under hot and humid tropical condition. According to the British Soil Classification Standard (BSCS), the studied tropical residual soil was classified as Clayey Sand and the corresponding physical properties were summarized in Table- I. The soil specimens having a nominal dimeter of 50 mm and height of 100 mm were prepared by dynamic compaction method in the laboratory. Dry soil density of 1550 kg/m^3 and moisture content of 14 % was used to prepare the soil specimens in the present study. Herein, the largest particle size was limited to 5 mm.

Table- I: Physical properties of tropical residual soil

Tests	Properties
Particle Size Distribution	Gravel = 19%; Sand = 41%; Silt = 37%; Clay = 3%
Atterberg Limit Test	LL = 32.60%; PL = 20.64%; PI = 11.98%
Proctor Compaction Test	MDD = 1799kg/m^3 ; OMC = 15%

B. Triaxial Testing System with AE Measurement

Mechanical properties of soil can be investigated accurately in a monotonic triaxial testing system involving precise control of pneumatic and hydraulic pressures. Figure 1 shows the experimental setup of a triaxial testing apparatus, which was specially devised to accommodate an AE transducer in the base pedestal. An overall experimental setup in the laboratory could also be seen in Figure 2.

Original triaxial cell was instrumented for conventional stress-strain-time measurement, including load cell, linear displacement transducer (LVDT), pressure transducer, and volume change device. The pore-water pressure and volumetric change measurement were monitored through strain-gauge type transducers from which the digital output signal could be obtained. During the test, the pneumatic pressure was controlled by continuously sending analog signal (0 to 5 V) to the Electro-pneumatic transducer from a computer equipped with NI board (PXI 6024) type of microcontroller.

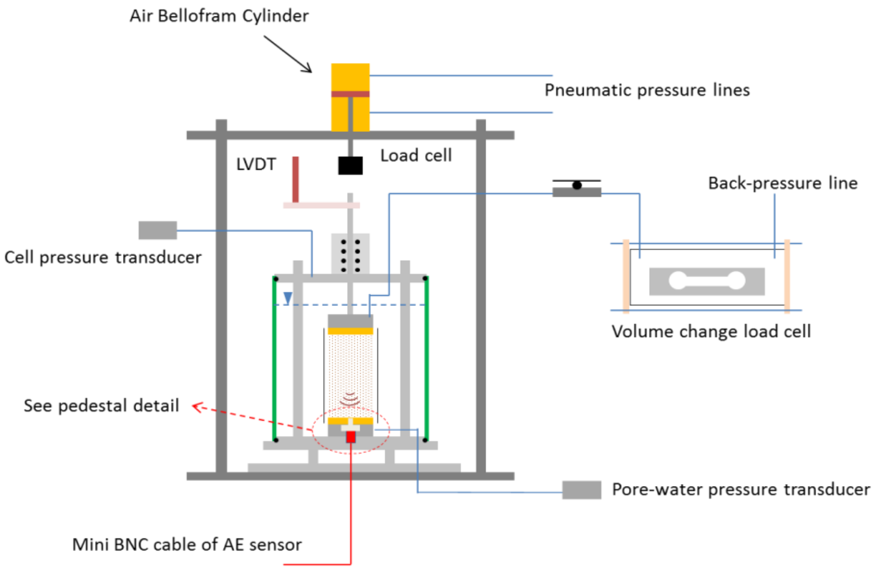


Fig. 1. **Schematic for triaxial testing apparatus instrumented with AE transducer**

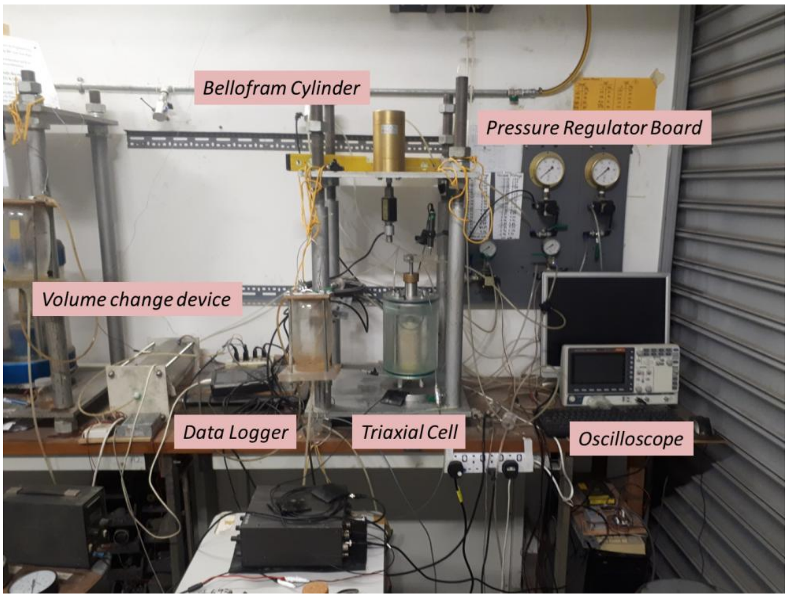


Fig. 2. Photographs of the triaxial testing system

The triaxial apparatus was equipped with a Bellofram cylinder (SC type Fujikura Bellofram cylinder) to facilitate stress-controlled loading condition. Tanimoto and Tanaka [12] also used the similar loading setup to avoid mechanical noise and applied constant rate of loading slowly. Smooth and frictionless axial movement could be attained by allowing an air pressure difference between the top and bottom diaphragm rubber inside the Bellofram cylinder. Continuous small increment of vertical stress was applied through the E/P transducer until the soil specimen reached its failure state at large strain amplitude. To further ensure a frictionless movement, the loading ram of the triaxial cell was made of a stainless steel rod with special surface treatment so as to reduce the mechanical noise caused by the friction between loading ram and linear bearing inside the loading shaft.

C. Fabrication of AE Base Pedestal

Figure 3 shows the detailed configuration of the base pedestal in which an AE transducer can accommodate. The selected AE transducer was known as a voltage-output type of piezoelectric accelerometer that had a built-in preamplifier inside the transducer casing. Specifically, the accelerometer belongs to a model of PA 12C being manufactured by Fuji Ceramics Corporation. As can be seen from Figure 3, the nominal height of transducer was 25 mm while the edge-to-edge diameter of the top hexagon surface was 12 mm. In principle, the sensor can sensitively detect micro-level vibration and convert the physical vibration to electrical output along the longitudinal direction of the transducer. This was made possible by the piezo-electrical mechanism acting at the piezo-ceramic disc inside the transducer. The resonant frequency of measurement for this particular sensor is central at 32 kHz and responsive over a wide range of frequency (between 100Hz and 100 kHz). It was speculated that stress waves as generated by the soil movement can propagate through soil grains structure as well as the pore water when a saturated soil was compressed or sheared.

As the frequency of reported AE signal being generated by soil mobilization was normally below 10 kHz [11] – [14], the selected AE transducer is suitable and can be used for the investigation of soil in this study.

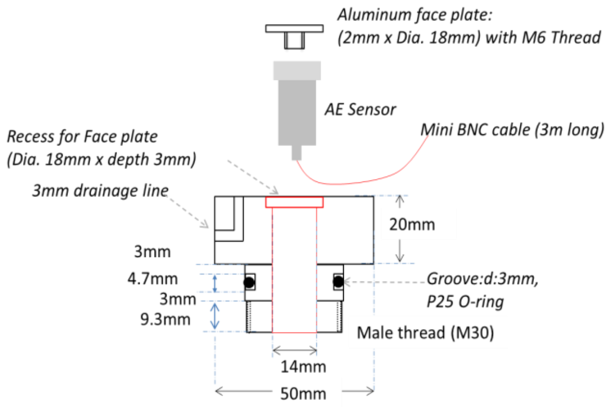


Fig. 3. Design details for the base pedestal accommodating AE transducer

Aluminum was selected as the material for AE base pedestal as it was understood that sound wave can propagate sufficiently fast in aluminum (i.e. 6300 m/s), as distinguished from a majority of engineering materials. As can be seen from the configuration, a center through hole having a nominal diameter of 14 mm was allowed for housing the AE transducer. An aluminum face plate, which was connected to the AE sensor, was devised to be in touch with a porous stone. The face plate was adhered to a shallow recess (3 mm) by using high strength flex glue, which can provide a rubberized, waterproofing, and durable sealing contact. Similar application of this kind of adhesive material could also be found in strain-gauge type of load cell where a flexible sealing could facilitate electrical resistance change in each strain gauge element. After a curing duration of one week, waterproofing ability was examined inside a triaxial cell being filled with pressurized water. It was found that the assemblage was waterproofed even up to a water pressure as high as 5 bar (i.e. 500 kPa).

On top of that, a 3 mm drainage hole was drilled to a depth of 15 mm below the contact surface of base pedestal so as to facilitate precise pore-water measurement and accomplishment of system compliance. The outlet of drainage hole was allowed at the sideway of base pedestal. A threaded PICSO tube fitting was used to connect the drainage hole and the polyurethane tube (outer diameter of 2 mm and inner diameter of 1 mm). It should be noted that the location of the tube fitting have to be approximately 15 mm below the top surface of base pedestal so as to allow tightening of O-ring onto a sleeve of rubber membrane (thickness of 0.2 mm) during the soil specimen assembling stage. Figure 4 shows the procedure of installation the AE transducer into the aluminum base pedestal. Firstly, one end of the mini BNC cable was connected to the AE transducer. It was later screwed into the male thread of aluminum face plate to form a solid assemblage.

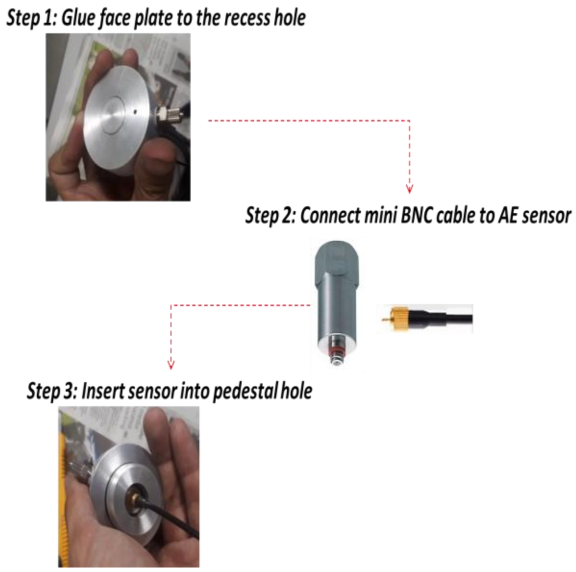


Fig. 4. Procedure of installing AE transducer into base pedestal

Since the base of soil specimen was placed on top of a porous layer to allow the drainage of pore water, it is crucial to devise a base pedestal that can sensitively collect the true AE signal as generated from the soil specimen. Tanimoto and Tanaka [12] used a more expensive metallic porous layer (also known as sintered porous metal filter) to facilitate the AE signal receiving. Lord and Koerner [11] suggested two approaches to facilitate direct AE signal measurement, including protrusion of a metallic waveguide into the soil specimen; and embedding the AE transducer into the center of larger soil specimen. In the present study, it was decided to adopt a composite porous filter taking into account of the cost-effectiveness as well as not to disturb the body of soil unfavorably. To facilitate a more direct AE measurement, the center hole of a porous stone was fitted with an aluminum plate (18 mm diameter x 5 mm thickness). Figure 5 shows the pictures of the modified porous stone that was formed by press fitting a thin aluminum plate into the center hole of porous stone. As will be explained in the subsequent section, the metallic-porous stone composite was evidenced to be effective in collecting the AE signal as generated by the mobilization of soil particles.

Fig. 5. Composite porous stone for AE study

D. Data Acquisition System

Figure 6 depicts a comprehensive data acquisition system to measure the conventional soil responses and acoustic emission signal. Since the output voltage signal being measured was initially weak, an amplifier was required for signal conditioning purpose. A TEAC amplifier with a model name of SA16 was used to amplify the analog signal.

The amplifier was fed with a supply voltage of 12 V through a DC power supply, which could guarantee a stable voltage supply during the experiment. It should be noted with care that a step down transformer was required for the DC power supply device as the exciting voltage was limited to 100 V only.

Through the amplifier device, the voltage of analog signal could be increased with a gain factor of 500 and the output signal could then be acquired. With the present instrumentation setup, an output line was used for the real-time monitoring in a digital Oscilloscope, while another output line was assigned to connect into a laptop for recording purpose. The digital Oscilloscope, GWinstek GDS-1000B series, was characterized with a vertical resolution of 8 bit/ per division and a precise time resolution of 1 ns per division. The in-built analog-to-digital converter within the Oscilloscope was able to convert the obtained analog signal into digital data that could be monitored or logged through a USB cable.

Since the true AE signal for granular material was reported to be audible and usually characterized with frequency content below 10 kHz only [11] – [12], the mentioned digital Oscilloscope could be used to capture the continuous signal. According to the well-known Nyquist theorem, the acquisition frequency of device shall be at least two times higher than the maximum frequency of signal to be measured. Herein, the maximum measuring frequency of the Oscilloscope was 1 GHz and undoubtedly satisfied the requirement. A coaxial-type of Bayonet Neill–Concelman (BNC) shielding cable was used to transmit the digital signal from the amplifier device to the digital Oscilloscope. This could minimize the effect of electromagnetic inference towards the signal being transmitted through the cable.

In the second output line, the amplified signal was transmitted through a BNC- audio jack cable connecting to a laptop. The amplified analog signal was later digitized to its corresponding digital form and logged by using the sound card in laptop. Dell Inspiron 15R 5447-5437 sound card was built in the laptop and acted as analog-to-digital converter. The sampling frequency was set to 96 kHz in the present experiment. Alternatively, an external USB type of sound card chip could be employed in signal digitization. External USB sound card is commercially available with an affordable price and can provide a sampling rate as high as 96 kHz. With the existing setup, real-time monitoring and recording of AE signal could be achieved to favor post-data processing after the experiment.

III. AE SIGNAL PROCESSING

Before the triaxial experiments, noise monitoring was carried out to characterize the background noise in the laboratory. Figure 7 depicts a typical record consisting of true AE signal and the ambient noise. It could be seen that the noise profile was not only affected by the baseline drift as a consequence of low-frequency content, but also characterized with higher-frequency component. The spiky waveform in the noise was caused by the high frequency content. According to the Fast-Fourier Transform (FFT) analysis, the dominant frequency of noise was 60 Hz, which was caused by the electrical noise. A periodic air-compressor noise was also found to be devastated and able to mask the true AE signal. In spite of that, the air-compressor noise could still be eliminated in the post-processing stage as it occurred under a predictable fashion. The authors opined that the understanding of noise pattern can be beneficial for the subsequent data filtering.

Computer programs were utilized to manipulate the digitized data and extract the acoustic emission counts result. A graphical user interface (GUI) software, called Audacity, was used in the present study to record the real-time audio data. This open-source software allows real-time digitizing, recording, and playing back quality audio data. The original audio data, which could be either in the form of WAV or MP3 format, was later deposited into process able ‘TXT’ or ‘CSV’ format for further analysis.

After obtaining the data-type file, a series of signal analysis could be accomplished through another open-source, general-purpose, and scientific computation program, i.e. Python. Mathematical analysis, such as FFT, bandpass filtering, waveform peak detection, and threshold counting, could be carried out accordingly. Figure 8 depicts a detailed configuration of true AE signal and a distinguished noise threshold. It could be observed that the AE signal exhibited attenuation and characterized with a dominant frequency of 5000 to 6000 Hz. Therefore, the raw data was subjected to bandpass filtering with a bandpass frequency range from 100 Hz to 20 kHz.

The AE count was herein referred to the digital peak data points exceeding a pre-set threshold level, which was marginally greater than the background noise level. The stress-strain measurement was later correlated with respect to the AE counting measurement. Throughout the present study, cumulative AE counts were defined as the total counts of AE signal at a specific time instant.

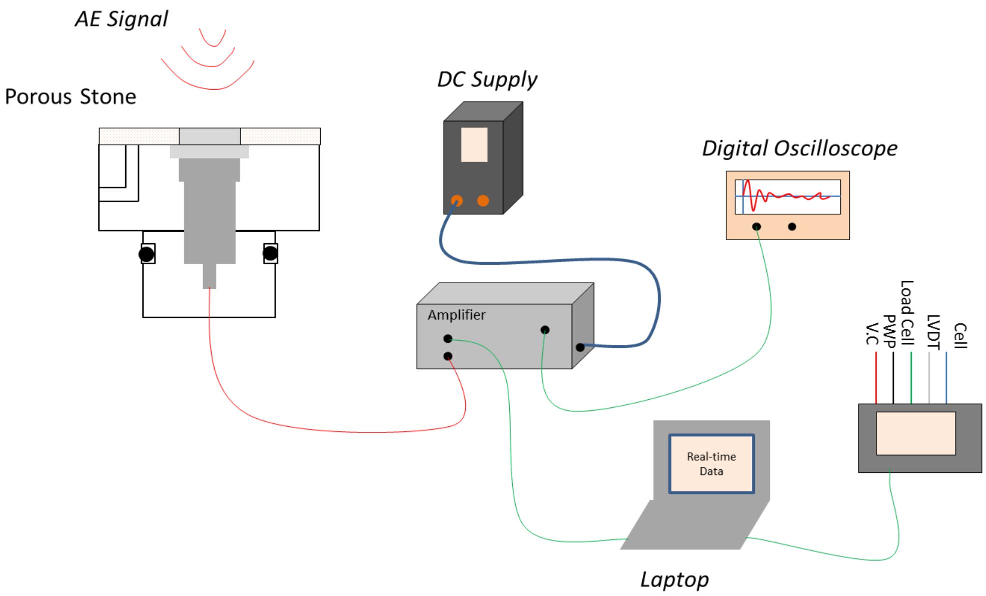


Fig. 6. Schematic of data acquisition setup for AE study

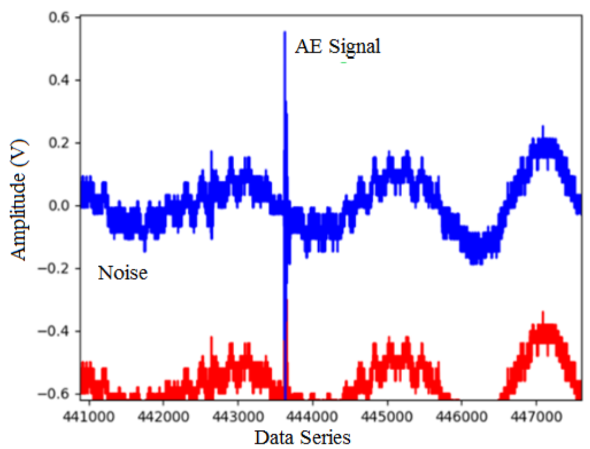


Fig. 7. Recorded AE signal and ambient noise

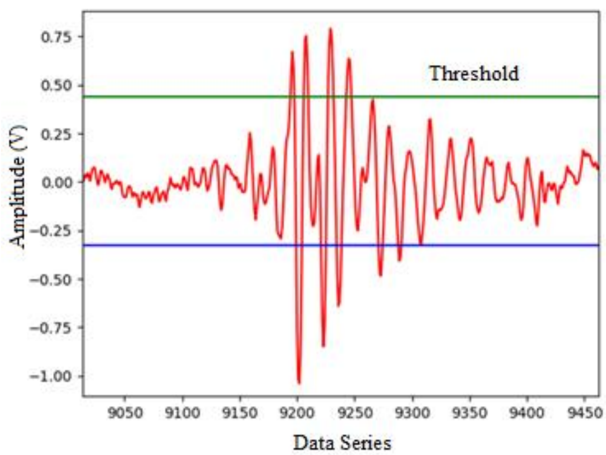


Fig. 8. Detailed AE signal and noise threshold

IV. RESULTS AND DISCUSSION

A. Isotropic Consolidation Test

Figure 9 depicts the experimental result of tropical residual soil tested under isotropic consolidation stage. The residual soil was consolidated isotropically under step-wise manner, with conventional stress-strain measurement and acoustic emission instrumentation being equipped. It was found that the residual soil started to emit noticeable AE at an effective consolidation pressure level of 43.5 kPa, implying the intrinsic pre-stress level as induced by the soil compaction process. This was consistent with the stress-strain measurement where the compressibility of soil was started to increase abruptly. When the soil was unloaded, no AE signal was detected. Once the soil was recompressed beyond the maximum pre-consolidation pressure, significant acoustic emissions were observable again and therefore the classical Kaiser's effect was evidenced. The recorded emissions implied that soil grains had been mobilized or slippage as a result of dissipating accumulated strain energy.

The isotropic consolidation results were in good agreement with the finding as reported by Tanimoto and Tanaka [12] in which soil yielding could be determined by the acoustic emission in addition to the stress-strain measurement. Moreover, it was undeniable that numerous weak AE signals (lower than the preset threshold level) could still be embedded in the acquired data and the compacted residual soil seemed to behave in ductile manner. For a brittle material, noticeable large-amplitude acoustic emissions can be recorded when the localized mobilization had been initiated and the stored energy being dissipated abruptly.

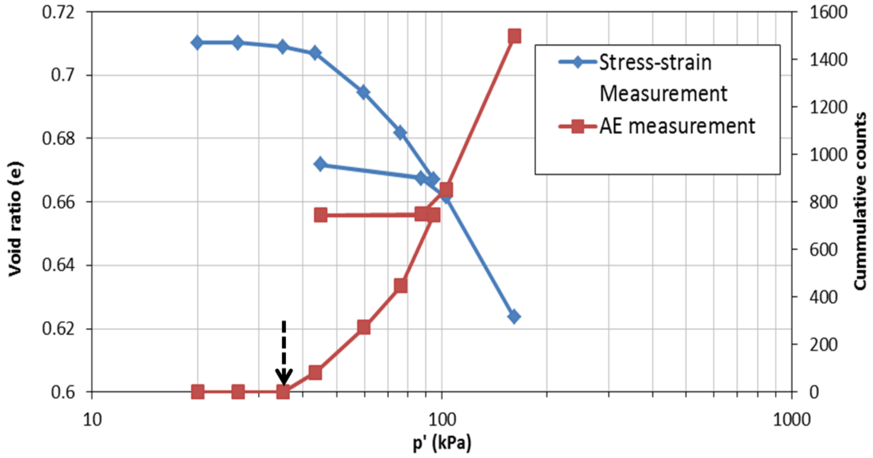


Fig. 9. Isotropic consolidation response of the studied tropical residual soil

On the other hand, a steady rise in small-amplitude AE could be seen from a more ductile material showing plastic behavior [17]. Subsequently, the response of residual soil when subjected to deviator stress was further examined.

B. Undrained Compression Test

During the undrained compression test, the cell pressure was kept constant while continuous deviator stress was exerted axially toward the soil specimen. For a particular type of granular material, a slow strain rate of straining is vital to ensure equalization of pore-water pressure within the soil specimen. JGS standard [18] suggested a strain-rate of 0.1 % / min for sandy material under undrained shearing condition. Throughout the undrained compression process, the residual soil specimen was sheared continuously at a constant stress-controlled rate of 0.07 % / min. It should be noted that the soil specimen was consolidated to a mean effective pressure of 40 kPa only in order to preserve the pre-consolidation effect as contributed by compaction during soil preparation stage. It is intended to observe the initial yielding of compacted soil before the soil had become fully compressible.

Figure 10 shows the relationship between deviator stress, total counts, and axial strain measurements. It was apparent that the experimental curve being plotted with respect to the cumulative AE counts could resemble the typical stress-strain relationship. The cumulative counts was well corresponded to the axial strain parameter. Similar findings for a wide range of geomaterials were also realized by Koerner et al. [14, 19]. After the soil reached an axial strain level of nearly 1.0 %, the soil specimen seemingly exhibited strain-softening and could deform plastically under constant stress.

On top of that, it could be recognized that noticeable acoustic emission signals could be measured once the yielding point was incipient to occur [12]. From Figure 11, it was apparent that initial yielding could occur at small strain level (i.e. 0.1%) by the abrupt increase of AE response and implying the soil no longer exhibited linear elastic behavior. It should be noted that AE counts were not directly proportional to the increase of deviator stress, possibly attributed to the fluctuation of supplied air pressure to the axial loading system. This might be improved by the adoption of much smaller constant stress-controlled rate, especially within the small-strain loading stage. In a nutshell, the properties of studied tropical residual soil as obtained from the AE measurement could be summarized in Table- II. On top of the pre-consolidation stress, the yield strain and stress could also be obtained from the AE measurement in undrained compression test.

Table- II: Soil properties as obtained from AE

Properties	Value
Frequency content	5 – 6 kHz
Pre-consolidation stress	43.5 kPa
Yield strain	0.1 %
Yield stress	30 kPa

Jardine [7] reported three phases of soil state development, such as linear elastic, non-linear elastic and plastic states for granular soils showing three kinematic yielding surfaces with the soil specimen being equipped with small-to-large strain measurement instrumentation. However, the expected kinematic yielding points could not be distinguished easily by relying on the AE measurement alone. This observation implied that a much slower rate of loading was required to obtain a more detailed AE response at small-strain range. Although progressive yielding points could not be obtained directly in this study, it was encouraging that irreversible AE response could be measured at the onset of yielding. Moreover, Figure 11 shows the similar relationships with cumulative counts being correlated to the deviator stress and pore-water pressure. Herein, the AE response was corresponded with the stress parameter, instead of the axial strain. It could also be observed that the soil specimen started to emit AE signal at previously-stated strain level. With the progress of shearing stress, the acoustic emissions increased with respect to the strain amplitude. Upon attaining large strain amplitude, immense AE signal could be captured owing to the active soil grains mobilization.

It is worth mentioning that the total AE counts number as obtained from the studied residual soil was similar to the clayey silt, as reported by Koerner et al.

[14]. It was understood from the previous study that soils with greater fines content could dissipate less AE energy than those of sand at a particular stress level.

The AE responses could also be influenced by other kind of factors, such as grain size, angularity, plasticity index, confining pressure, and etc. In view of the fact that yielding could be justified, the developed experimental AE measuring setup could be used to facilitate the investigation of AE response of soil. It was also acknowledged that progressive parametric studies were essential to be carried out to form a coherent understanding on the tropical residual soil.

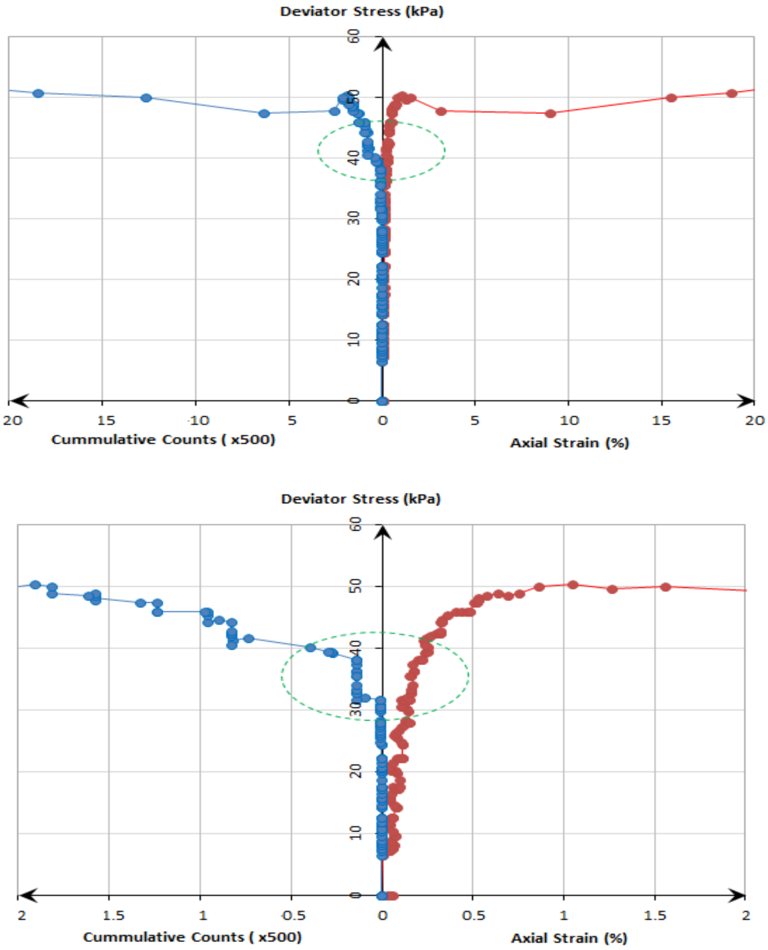
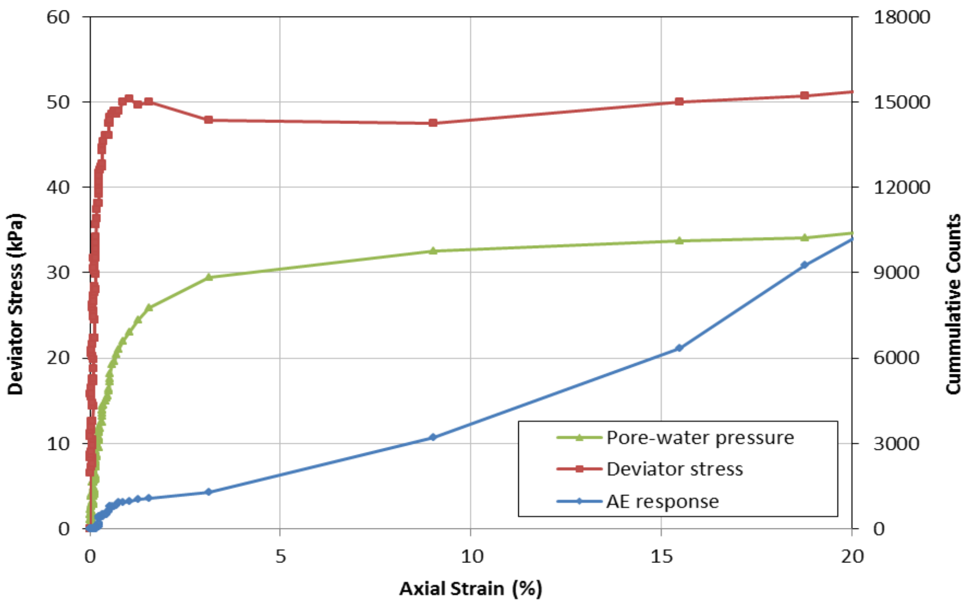


Fig. 10. Relationship between deviator stress-strain-AE at large and small strain range



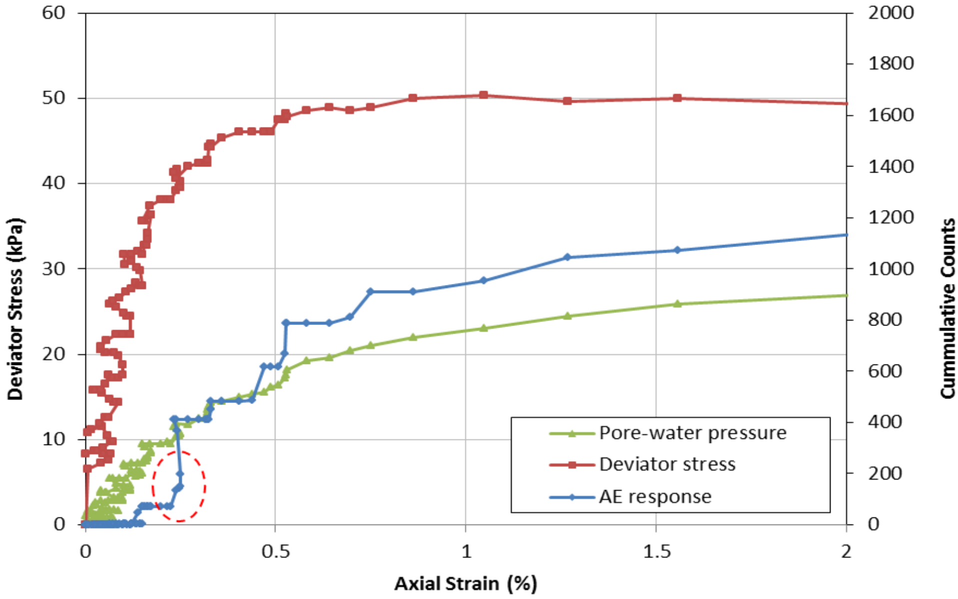


Fig. 11. Deviator stress, pore water pressure, and AE measurement at large and small strain rang

V. CONCLUSION

From the present experimental study, several concluding remarks could be drawn as follows:

1) The developed acoustic emission measuring system was evidenced to be effective to facilitate the non-destructive investigation towards the states change of tropical residual soil under isotropic consolidation and undrained shearing conditions.

2) The acoustic emission measurement was closely related to the mechanical responses of the studied tropical residual soil. Kaiser's effect was evident from the experimental results of isotropic consolidation test and positively corresponded to the stress-strain measurement. Also, the effective pre-consolidation pressure was able to be determined from the AE measurement during the isotropic consolidation stage.

3) The AE responses were satisfactorily corresponded to the axial strain parameter. With the progress of undrained compression, the cumulative counts were increased with respect to the measured strain level. Cumulative number of emission as obtained from the studied tropical residual soil was also similar to the soil with fines, as reported by others.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial supports from the Universiti Tunku Abdul Rahman Research Fund (IPSR/RMC/UTARRF/2017-C1/L06). Assistances in the fabrication of triaxial apparatus from Mr. Ho were always highly appreciated.

REFERENCES

1. G. R. McDowell, M. D. Bolton, and D. Robertson, "The fractal crushing of granular materials," J. Mech. Phys. Solids. 44(12), 1996, pp. 2079-2102.
2. W. W. Mao, S. Aoyama, S. Goto, and I. Towhata, "Acoustic emission monitoring of sandy ground under sequential pile loading," International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE), 2015.
3. W. L. Lin, W. W. Mao, J. Koseki, and A. Liu, "Frequency response of acoustic emission to characterize particle dislocations in sandy soil," International Conference: Fundamentals of Soil Behaviours, 2018, pp. 689–697.
4. G. Viggiani, "General Report of TC 105 Geomechanics through the scales," Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, 2013.
5. P. Bullock, and C. P. Murphy, "The microscopic examination of the structure of sub-surface horizons of soils," SAGE Journals, 8(6), 1976.
6. R. Dyvik, and T. S. Olsen, "Gmax measured in oedemeter and DSS tests using bender elements," International Conference on Soil Mechanics and Foundation Engineering, 12 Rio de Janeiro 1989. Volume 1, 1989, pp. 39-42.
7. R. J. Jardine, "Some observations on the kinematic nature of soil stiffness," Soils and Foundations, 32(2), 1992, pp.111-124.
8. M. Oda, "Deformation mechanism of sand in triaxial compression tests," Soils and Foundations, 12(4), 1972, pp. 45-63.
9. M. A. Hamstad, "A review: acoustic emission, a tool for composite-materials studies," Experimental Mechanics, 1986.
10. D. Lockner, "The role of acoustic emission in the study of rock fracture," International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 30(7), 1993, pp. 883-899.
11. R. M. Koerner, and A. E. Lord, Jr., "Acoustic emissions in medium plasticity clayey silt," Proc. ASCE J. Soil Mech. and Found. Div. 98, 1972, 161- 165.
12. K. Tanimoto, and Y. Tanaka, "Yielding of soils as determined by acoustic emission," Soils and Foundations, 26 (3), 1986, 69-86.
13. R. Koerner, A. Lord, W. McCabe, and J. W. Curan, "Acoustic emission behaviour of granular soils," J. Geotech. Eng. Div, ASCE, Vol.102, GT7, 1976, pp. 761-773.
14. R. Koerner, W. McCabe, and A. Lord, "Acoustic emission behavior and monitoring of soils," in Acoustic Emissions in Geotechnical Engineering Practice, ed. V. Drnevich and R. Gray (West Conshohocken, PA: ASTM International, 1981), 93-141.
15. S. Goto, F. Tatsuoka, S. Shibuya, Y. S. Kim, and T. Sato, "A simple gauge for local small-strain measurements in laboratory," Soils and Foundations, 31(1), 1991, 169-180.
16. A. W. Bishop, and D. J. Henkel, "The measurement of soil properties in the triaxial test," E. Arnold, London, 1962.
17. W. Swindlehurst, "Acoustic emission- 1 Introduction," Non-Destructive Testing, 6(3), 1973, 152-158.
18. Japanese Geotechnical Society Standards: Laboratory Testing Standards of Geomaterial, Vol.1.
19. A. Smith, and N. Dixon, 2019. "Acoustic emission of dense sands," Géotechnique, Doi:10.1680/jgeot.18.p.209.

AUTHORS PROFILE

Lim Jun Xian, is currently a PhD candidate in Universiti Tunku Abdul Rahman. He investigated the dynamic behaviors of tropical residual soil during his Master degree. In his PhD study, he focuses on the stress-strain-time and wave propagation properties of tropical residual soil in Malaysia.

Dr. Chong Siaw Yah, received her PhD from Universiti Teknologi Malaysia. She works as an assistant professor in the department of civil engineering, Universiti Tunku Abdul Rahman. Her main research interests focuses on the soil stabilization and investigation of mechanical behaviours on tropical residual soil, and etc.

Prof. Dr. Yasuo Tanaka, received his Master degree from University of Manitoba (Canada) and PhD from University of Sheffield (UK). He is currently appointed as an adjunct professor of Civil Engineering at Universiti Tunku Abdul Rahman. His research interests include geotechnical earthquake engineering, disaster risk reduction, acoustic emission testing, and etc.

Dr. Ong Ying Hui, received her Master degree and PhD from University of Malaya in 2010 and 2014, respectively. Dr. Ong is currently an assistant professor in Universiti Tunku Abdul Rahman (chemical engineering department). She is also a graduate member of IEM and BEM. Her main research interests are environmental engineering, waste water reuse, nutrient/ energy recovery, bioconversion, and etc.