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EFFECT OF FINE CONTENT ON SOIL DYNAMIC PROPERTIES

J. X. LIM, M. L. LEE*, Y. TANAKA

Department of Civil Engineering, Lee Kong Chian Faculty of Engineering and Science,
Universiti Tunku Abdul Rahman, 43000, Kajang, Selangor DE, Malaysia
*Corresponding Author: mllee@utar.edu.my

Abstract

Dynamic properties of soil have attracted an increasing attention among geotechnical engineers in Malaysia owing to the frequent earthquake incidents reported recently and the demand of high speed railway infrastructures. The present study investigated the effect of fine content on the soil dynamic properties based on three selected soils in Malaysia. One sand mining trail (i.e. silty sand) and two tropical residual soils (i.e. sandy clay and sandy silt) were tested on a 1 g shaking table. The experimental shear moduli were compared with the established degradation curves of sandy and clayey soils obtained from literature. The shear moduli attenuated with the increase of shear strain amplitude for the three soil samples. The amount of fine content in the soil was found to be a more dominant factor affecting the dynamic properties of soil compared with the plasticity and geological characteristics of the soil. The experimental shear moduli of sandy silt were similar to that of sandy clay. It may be attributed to the fact that the two studied residual soils have a similar amount of fine content. In addition, the shear moduli of the studied residual soils could not be fitted to the degradation curves of sand and clay which have been well studied in the past. The residual soils constituted unique dynamic properties that worth further investigation.

Keywords: Dynamic properties, Secant shear modulus, Tropical residual soils, Shaking table test, Fine content.

1. Introduction

Peninsular Malaysia is seismically affected by the far-field tremors and earthquakes from neighbouring countries like Indonesia and Philippines. Some of the notable earthquake incidents in the Southeast Asia region include the 2004 Aceh earthquake, the 2005 Nias earthquake, the 2000 Bengkulu earthquake, the 2015 Sabah earthquake, etc. [1]. The occurrences of seismic activities in Malaysia have attracted an increasing attention from the public and authorities.

Nomenclatures

G	Secant shear modulus, MPa
G_{max}	Maximum shear modulus, MPa

Greek Symbols

γ	Shear strain amplitude
$\Delta\gamma$	Shear strain range
$\Delta\tau$	Shear stress range, kPa.

Abbreviations

LL	Liquid Limit
PI	Plasticity Index
PL	Plastic Limit

Earthquake waves are normally transmitted through soil. In general, soil can be grouped into transported soil and residual soil. The formation of soils largely depends on the topography, climate, and nature of the parent rock [2]. Residual soils are formed from rock (i.e., igneous, metamorphic, and sedimentary) or accumulation of organic material and remain at the place where they were formed [2]. Malaysia, being a tropical country with warm and humid climates, has abundant of tropical residual soils which are formed through intense physical and chemical weathering processes. Intense rainfall, high humidity and temperature have contributed to a thick residual soil deposit in the country [2].

Numerous researches have been extensively conducted on the hydraulic properties, compressibility, stiffness, and shear strength properties of residual soils for various engineering applications [2-4]. Several studies on dynamic behaviours of residual soils have also been reported from different parts of the world [5-7] However, studies on dynamic behaviours of tropical residual soils in Malaysia are still very limited [7]. Therefore, this area of research needs to be carried out progressively to enrich the database of dynamic properties of soils in Malaysia which would be essential for solving geotechnical earthquake engineering problems through analytical or numerical solutions.

Over the years, many researchers have conducted experiments related to the shaking table tests for a wide variety of soil materials [7-11]. Kazama and Yanagisawa [10] conducted dynamic centrifuge shaking table tests on a saturated soft clay. Accelerometers were installed at the surface of the soil container while pore water pressure transducers were installed along the height of the soil internally. The measured acceleration records were processed by using the low-cut filtering approach to avoid a baseline drift when performing the integration. Tanaka and Lee [7] conducted a 1 g shaking table test on a sandy soil in Malaysia. The soil specimen which originated from the Kenny Hill Formation was compacted to a designated volume in which the soil condition in a compacted embankment could be reproduced. A number of accelerometers were installed to monitor the changes of acceleration with time and baseline correction was performed to avoid the baseline drift.

Hardin and Black [12] reported a number of factors that may influence the shear modulus and damping ratio of soils. Those factors include effective confining pressure (effective mean principal stress), void ratio, degree of saturation, soil type, over-consolidation ratio, number of loading cycles, shear strength parameters, and shear strain amplitude. It is well known that the dynamic properties of sandy soils are influenced by the effective confining pressure and density of soils [19], while the effects of plasticity index and strain rate were found to be profound in fine-grained soils [13, 14].

This study aims to investigate the effect of fine content in natural tropical residual soils on their dynamic properties. Soil samples were collected from three selected sites in Malaysia for the 1 g shaking table tests. Shear moduli of the soils were computed from the experimental acceleration records. The results were then compared with the established degradation curves of sandy and clayey soils obtained from literature [14, 19] in order to justify whether the studied residual soils are inherent with the behaviour of those sandy and clayey soils.

2. Material and Methods

This section presents the soil sampling works and physical properties of the three selected soils in the present study. The experimental setups for the 1 g shaking table and the relevant instrumentations are described in detail.

2.1. Geological formations and physical properties of studied soils

In the present study, a sand mining trail (soil A) and two tropical residual soils (soil B and soil C) were sampled for a detailed investigation into their dynamic properties in laboratory. Disturbed residual soils were sampled from the superficial layer of soil deposit at a depth of 2 m below the ground surface. Figure 1 shows the geological formation and distribution of tropical residual soils in Peninsular Malaysia [2]. In general, the residual soils in Peninsular Malaysia can be grouped into two categories, namely granitic residual soil and sedimentary residual soil. Based on the locations of the sampling sites as shown in Fig. 1, the two tropical residual soils (i.e. Soil B and Soil C) originates from the sedimentary rock. In specific, the soil deposit of Kajang formation (Soil B) belongs to a metasedimentary rock formation which consists of schist and phyllite [15]. The soil in Simpang Renggam area (Soil C) originates from a clastic sedimentary rock formation which consists of shale material [16]. In tropical countries, schist and shale would produce mostly silty materials or soils with illitic clay minerals. Apart from the physical weathering process, chemical weathering is prevalence in hot and humid regions in which the rock is decomposed into silty or clayey residual soils [2]. In terms of the geological age of rock, the Kajang schist is within the Silurian and Ordovician periods, whereas the rock of Simpang Renggam is in the middle to late Permian period. The Permian period is earlier than the Silurian and Ordovician period [17].

The soil physical tests were subsequently conducted in compliance with the procedures as stated in the British Standard, BS 1377 [18]. The physical tests included wet sieving, hydrometer analysis, Atterberg limit tests, and proctor compaction test. Table 1 shows the physical properties of the soils. The soils A, B and C were classified based on the British Soil Classification System (BSCS) as very silty sand (SML), sandy clay (CHS), and sandy silt (MIS), respectively.

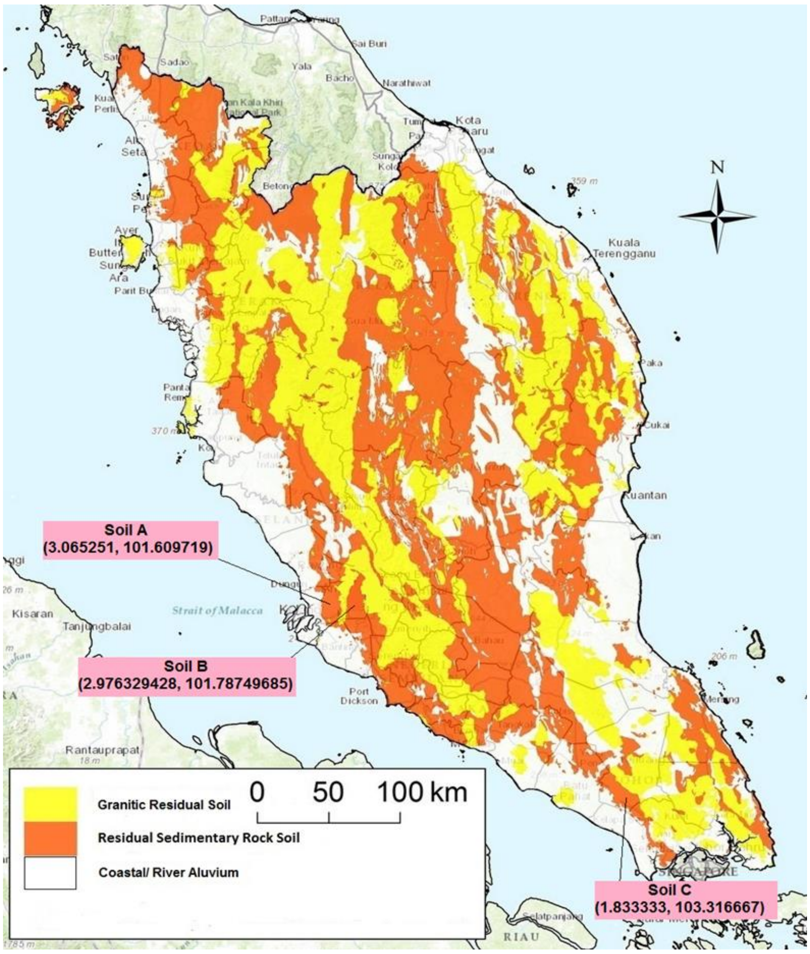

Fig. 1. Distribution of tropical residual soils in Malaysia [2].

Table 1. Physical properties of soils.

Properties	Soil A	Soil B	Soil C
Composition			
Gravel	13%	0%	12%
Sand	57%	46%	30%
Fine Content	30%	54%	58%
Plastic Limit (PL)	19.9	22	27.5
Liquid Limit (LL)	24.5	68	45.5
Plasticity Index (PI)	5	46	18
Soil Classification	Very Silty Sand (SML)	Sandy Clay (CHS)	Sandy Silt (MIS)
Maximum Dry Density	1970 kg/m^3	1570 kg/m^3	1640 kg/m^3
Optimum Moisture Content	11.8%	23%	20.8%
Void Ratio (compacted soil)	0.345	0.688	0.616
Degree of Saturation (compacted soil)	90.63%	88.59%	89.48%

2.2. Shaking table

A 1 g shaking table machine was used to investigate the dynamic responses of soils under a series of designated shaking motions. Figure 2 shows the schematic diagram of the shaking table system. The direct-drive motor was used to produce a one-dimensional shaking motion on a levelled shaking table platform (2 m by 2 m) by generating a mechanical torque repeatedly. The shaking table platform was lifted upward by supplying an air pressure of 2 bars to the bottom of the platform. A series of input motions were attempted as tabulated in Table 2. The input motions were governed by the input frequency and linear displacement of the shaking table. The input frequency was verified to be consistent with the response of shaking table, whilst the input displacement was found to be incompatible with the actual linear displacement [7]. It follows that the unit of input linear displacement was designated as unit of displacement prior to the test.

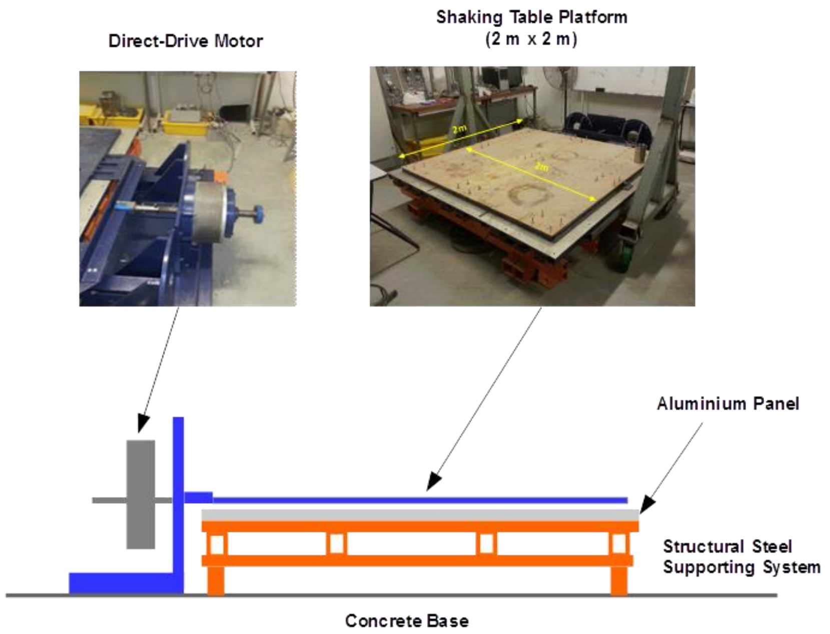

Fig. 2. Shaking table.

Table 2. Input motions for shaking table test.

Test No	Input Motion Frequency (Hz)	Input Motion Displacement (unit of displacement)
1	0.1	0.5
2	0.1	2
3	0.5	2
4	1	1
5	1	2
6	2	0.5
7	2	1
8	5	0.4
9	5	0.5
10	20	0.1

2.3. Instrumentation & data acquisition

Figure 3 shows the schematic diagram of the soil model tested on the 1 g shaking table. Three layers of aluminium shear stacks and a thin rubber membrane were used to contain the soil sample. For sample preparation, the soil was compacted to 95% of the maximum dry density. A wood tamper, which was coated with a layer of latex, was fabricated to compact the soil sample into six successive layers. The interface between soil layers was scratched to minimize heterogeneity in the compacted layers of soil. A plywood panel was placed on top of the compacted soil model. Nails were protruded approximately 3 mm into the soil sample in order to reproduce shear stress induced by inertia force from the surcharge loading. The surcharge loading (i.e. 10 kPa) was formed by a timber box containing sandbags and steel plates. A surcharge loading weighing 1000 kg can reproduce an overburden pressure of 10 kPa.

Three units of TML accelerometers (model: ARH-20A) and five units of KYOWA accelerometers (model: ASW-2A) were used in the experiment. The TML accelerometer (as shown in Fig. 4) has an acceleration measuring range from 10 m/s^2 to 500 m/s^2, while the KYOWA accelerometer has an acceleration measuring range from 9.807 m/s^2 to 196.1 m/s^2. The accelerometers were connected to a TML data logger for enabling data storage in a computer. Seven accelerometers were embedded at the centre of the soil model from the base to the top surface at a height interval of 3.5 cm in order to evaluate a complete displacement profile along the sample height. In addition, an accelerometer was attached on the surcharge loading container to measure the acceleration induced by the surcharge loading when the soil model was subjected to a shaking motion. By knowing the acceleration trace of the surcharge loading, the inertia shear force or shear stress applied on the soil can be computed.

A laser displacement sensor (model: OPTEX FA CD5-85, as shown in Fig. 5) was used to measure the linear displacement of the shaking table platform. The measurement can be compared with the displacement derived from the accelerometer attached on the base of the shaking table for verification purposes. The laser displacement sensor has a measuring range of 85 ± 20 mm with a measuring resolution of 1 μm and a minimum sampling interval as low as 100 μs.

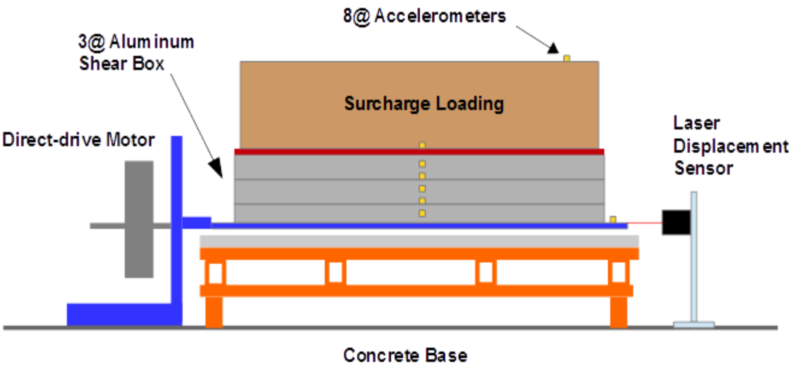

Fig. 3. Schematic of shaking table test.

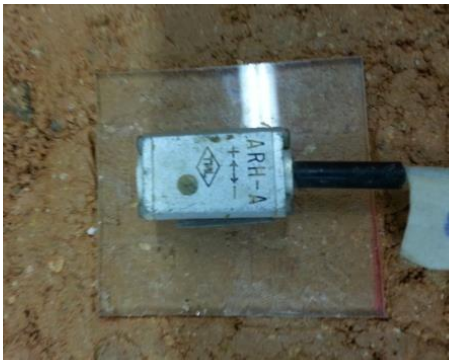

Fig. 4. Accelerometer.

Fig. 5. Laser displacement sensor.

3. Data Processing

In the data processing stage, the raw acceleration data were processed and adjusted before used for integrating displacement data. Digital band-pass filtering and numerical integration methods were applied on the experimental acceleration data. The bandpass filtering approach has been widely applied in signal processing [8, 19].

From the processed data, shear stress and shear strain profiles were determined. It follows that a series of stress-strain relationships or hysteresis loops were established. Lastly, secant shear modulus and damping ratio were evaluated from the obtained hysteresis loops (as shown in Fig. 6). Equation (1) shows the equation used to compute the secant shear modulus of soil.

$$G = \frac{\Delta \tau}{\Delta \gamma} \tag{1}$$

where G = secant shear modulus, kPa, $\Delta\tau$ = shear stress range, kPa, and $\Delta\gamma$ = shear strain range.

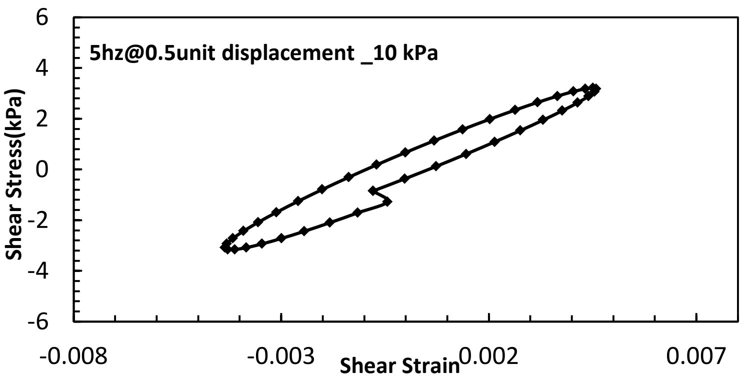

Fig. 6. Hysteresis loop.

4. Results and Discussion

The experimental data were compared with the established degradation curves for sandy soil and clayey soil, respectively [14, 20]. The degradation curves (as shown in Fig. 7) for clayey soil were established in accordance with the plasticity indexes (PI) of soils tested in the present study (PI of Soil A = 5, PI of Soil B = 46, PI of Soil C = 18). For normalizing the secant shear modulus, the maximum shear modulus was computed by using an empirical equation reported by Hardin and Black [12]. The computed maximum shear moduli ranged from 10.6 MPa to 23.7 MPa.

Equation (2) shows the formula used to predict the degradation curves for sandy soil [20]. Two hyperbolic curves (i.e. lower bound curve, and upper bound curve) were obtained for sandy soils.

$$\frac{G}{G_{\max}} = \frac{1}{\left[1+\left(\frac{\gamma-\gamma_e}{\gamma_r}\right)^a\right]} \tag{2}$$

where G = secant shear modulus, MPa, G_{max} = maximum shear modulus, MPa, γ = shear strain amplitude, %. For lower bound curve: γ_e = 0; γ_r = 0.02%; a = 0.88, and upper bound curve: γ_e= 0.003%; γ_r = 0.10%; a = 0.88.

Equation (3) shows the relationships between normalized secant shear modulus and shear strain amplitude for clayey soils [14].

$$\frac{G}{G_{\max}} = \frac{1}{\left[1+\left(\frac{\gamma}{\gamma_{ref}}\right)^{0.94}\right]} \tag{3}$$

where γ_{ref} = 3.7 (PI / 1000), and PI = Plasticity Index.

Figure 7 shows the plotting of shear modulus data points obtained from the present experimental study. The experimental data points were compared with the established degradation curves of sandy and clayey soils. It was found that the shaking table test on large samples could facilitate a movement of large shear strain amplitude only. Different testing setups should be used to obtain results of small shear strain which will be reported in another study. In general, the shear moduli attenuated with the increase of shear strain amplitude. This finding agreed with most of the published literature [12, 14, 20]. At a large strain level, the shear modulus data points were close to the lower bounds of the established curves for both sandy and clayey soils. However, there was no direct relationship between shear modulus and soil type (sand, silt or clay) among the three selected soils. The results showed that the shear moduli of soil B were similar to that of soil C despite of the fact that Soil B is of clayey material and Soil C is of silty material. It was noted that the amount of fine content for both of the soils were close to each other (54% for Soil B and 58%, for Soil C). For Soil A with a fine content of 30%, the gradation curve was visibly lower than the soils with higher fine contents (Soil B and Soil C).

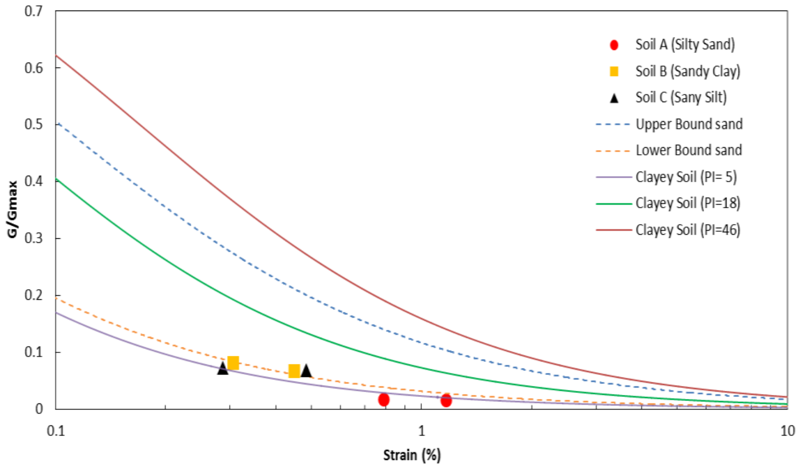

Fig. 7. Degradation curves.

It has been well-agreed that the dynamic properties of clayey soils are predominantly affected by their plasticity index, while the dynamic properties of sandy soils are dependent on their void ratio and degree of saturation [13, 14, 20]. It was observed that the residual soils tested in the present study (Soil B and Soil C) behaved neither as a clayey material nor a sandy material. The residual soil can be regarded as a unique material in which their dynamic properties worth further investigation. It appears from the present preliminary investigation that the fine content of soil has a more profound effect on the shear moduli than other physical properties of the soils. From Fig. 7, it appeared that the degradation curve of Soil B was slightly higher than that of Soil C despite of the fact that the fine content of Soil B (54%) was marginally lower than Soil C (58%). This observation could be attributed to the plasticity index of the soil as established literature suggested that soils with a higher plasticity index would contribute to a higher degradation curve. Further investigation on the influence of fine content and other physical parameters on the dynamic properties of tropical residual soils has to be carried out. It was believed that a detailed study on microstructure and micromechanics of soils can facilitate the need.

5. Conclusions

The following conclusions are drawn from the study:

- The shaking table test in the study could facilitate large shear strain amplitude of movement in the soil dynamic test.
- The shear moduli attenuated with the increase of shear strain amplitude. At a large strain level, the shear modulus data points were close to the lower bounds of established gradation curves for both sandy and clayey soils.
- Based on the shear modulus obtained from the three soils tested in the present study, the fine contents of the soils were found to have a more profound effect on the shear moduli than other physical/ geotechnical properties of the soils. However, more detailed investigations should be carried out to further confirm this finding.

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