International Journal of Civil and Structural Engineering– IJCSE
Volume 3 : Issue 1 [ISSN : 2372-3971]
Publication Date: 18 April, 2016

Overviews of Factors Affecting Dynamic Properties of Tropical Residual Soil

Lee Min Lee, Zhao JianJun, Koo Kean Yong, Yang Chong Li

***Abstract*—Unexpected earthquake incidents and development of high speed railways in Malaysia have drawn increasing attention of studies on soil dynamic behaviours. This paper provides an overview of the factors affecting dynamic properties of soil, i.e. damping ratio and shear modulus. Confining pressure and frequency of cyclic loading are the main extrinsic factors affecting the dynamic properties of soil, while soil plasticity and percentage of fines are identified as the main intrinsic factors of soil influencing its dynamic behaviours. It is found that previous studies of soil dynamic properties mainly focus on sandy and clayey soils. Studies of dynamic properties for tropical residual soil that consists of predominantly silty materials are still very limited.**

***Keywords*—residual soil, dynamic behaviours, damping ratio, shear modulus, cyclic loading.**

I. Introduction

Despite of the fact that Malaysia is located on a seismically inactive region, the importance of seismic design particularly in urban areas that are dominated by high-rise buildings should not be overlooked. Malaysia is located at the peripheral of the ring of fire and next to two neighbouring countries i.e. Indonesia and Philippines which have seen violent episodes of seismological activities in the past few decades. Therefore, the chances of being jolted by at least one moderate earthquake in the country cannot be completely ruled out.

On 5th June 2015, an earthquake with a moment scale of 6.0 struck the north-western part of Malaysia, Sabah resulting in eighteen casualties (Fig. 1). The incident has created an alarming signal to the local engineers and authorities to put greater attentions to the dynamic stability of buildings. In addition, in conjunction with the government's initiative to develop modern and sustainable transport system, there are increasing numbers of high-speed railway lines being proposed in Malaysia. The vibration / dynamic cyclic loading induced by the high-speed railway may weaken the stiffness and strength of soil and results in excessive deformation in soil, and the supporting structures. These circumstances have resulted in increasing attentions putting on the studies of soil dynamic behaviours in Malaysia.

Lee Min Lee, Koo Kean Yong, Yang Chong Li
Universiti Tunku Abdul Rahman
Malaysia

Lee Min Lee, Zhao JianJun
State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (Chengdu University of Technology)
China

Figure 1. Occurrence of rockslide following the 6.0 moment scale earthquake in Sabah, Malaysia resulted in 18 killed

This paper reviews the soil profiles in Malaysia and discusses factors affecting their dynamic behaviours. The findings from the present study are useful for formulating subsequent experimental approaches for the study of dynamic behaviours of soils in Malaysia.

II. Tropical residual Soil

The Public Works Institute of Malaysia [1] defines that residual soils are soils that derived from the in-placed chemical weathering of parent rocks, which free from any significant distance of movement or transportation. Chemical weathering involves of various chemical process such as oxidation, hydrolysis, hydration, etc, which cause decomposition of the rock. In Hong Kong, definition of residual soil created by Brand & Philipson [2] is more preferable by the local engineers. They defined it as ‘a soil formed by weathering in place, but with the original rock texture completely destroyed’. Meanwhile, Blight [3] defines that all material of a soil consistency that is located below the local ancient erosion surface is residual soil. Fig. 2 shows a typical profile of tropical residual soil.

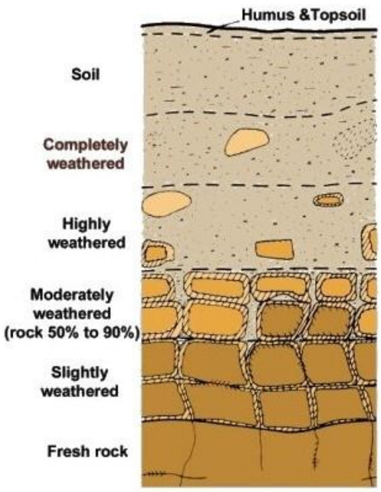

Figure 2. Typical profile of tropical residual soil [4]

Tropical residual soil is mostly found in tropical area enclosed between the latitudes 20° North and South of the Equator including Malaysia, Singapore, Philippines, Sri Lanka, Nigeria, Ghana and etc. These areas are having common characteristics, i.e. high temperature and heavy rainfall. This is due to the higher rate of weathering processes occur in high temperature and heavy rainfall regions.

In Malaysia, residual soils cover more than three-quarters of the land area of Peninsular Malaysia [5]. The land in Malaysia receives abundant rainfall throughout a year and resulting in massive physical weathering of rocks. Therefore, there is deep weathering profiles and intense formation of tropical residual soils in the country. The major composition of the residual soil in Malaysia is made up of sand, silt and clay. Each of them is combined in varying proportions depending on the geological settings of the soil [6].

The properties of residual soils are prominent criteria to be considered by engineers during planning stage of various engineering construction works. However, the properties of the residual soils are known to be highly heterogeneous and anisotropic subjected to degree of weathering of their parent rock. Review from the current literature suggests that unsaturated shear strength and hydraulic properties of tropical residual soils have been studied extensively by numerous researchers around the world. However, dynamic properties of the residual soils still receive very little attention from geotechnical researchers.

III. Dynamic Properties of Soil

Dynamic properties of soil are playing a vital role in the study of dynamic response of soil subjected to the dynamic loads. Generally, dynamic loads are produced by earthquakes, blasting, wind loading or machine vibrations. Different types of dynamic loads generate various level of strain. Since dynamic soil properties are strain level dependent, the effect of strain level is significant and mostly determined before choosing the appropriate methods to carry out dynamic soil properties tests. For instance, wave propagation represents the elastic properties of soil when strain level is less than 0.0001%, while larger strain levels manifest changes in deformation modulus, damping ratio, pore-water pressure or volume [7]. Thus various idealized models and analytical techniques, either in situ or laboratory tests, were established by many engineers and scientists to improve the results of dynamic soil properties at different strain level.

A. *Damping Ratio*

Damping is used to represent the ability of a material to dissipate dynamic load or dampen the system. Energy dissipation commences when soil deposits are subjected to dynamic loading and the amount of energy dissipated is showed by hysteresis loop of stress-strain curve.

Damping is usually manifested as damping ratio, ζ which is defined as the ratio of damping coefficient divided by the critical damping coefficient of the system. Damping ratio, ζ refers to the ability of a material to dissipate dynamic load. The higher the damping ratio, the more energy losses from the oscillating system enabling the system to return to equilibrium faster than an oscillating system with a lower damping ratio. For soil subjected to dynamic loading, the increasing cyclic shear strain amplitude leads to an increase in damping ratio. In a single degree of freedom system with viscous damping, the damping ratio is governed by equation

$$D = \frac{C}{C_C} = \frac{C}{2\sqrt{k \cdot m}} \quad (1)$$

Where,

C = damping coefficient
C_C = critical damping coefficient
k = stiffness
m = mass of the system,(kg)

The types of damping can be classified into 3 groups, namely over-damped for D > 1, critically damped for D=1 and under damped for D < 1.

The damping ratio of soil can be determined by various laboratory or in situ tests. Many researchers found that the damping ratio increases with increasing frequency vibration. However, Maxwell model shows the opposite result [7]. On the other hand, several researchers found that damping ratio is not much significantly affected by void ratio and number of cycles [8]. Based on the relevant researches, the value of damping ratio is usually in the range of 0.3 to 10.0 for various ground materials.

B. *Shear Modulus*

Shear Modulus, *G* is a very important parameter in analyzing seismic ground responses. It is defined as the ratio of shear stress with respect to shear strain. Shear modulus is one of several quantities that describe the tendency of a material to deform under loading, in particular, under shearing. There is a linear cyclic shear strain threshold, a strain limit in which once exceeded in a loading condition, the soil starts to exhibit non-linear behaviour. Thus when the soil is subjected to a cyclic strain below this limit, the shear modulus does not change. The shear modulus of a soil is at maximum when the cyclic shear strain is below the threshold. Accordingly, the term G_{max} is used to represent the shear modulus at this strain state. Beyond this threshold, the shear modulus starts to decrease with increasing cyclic shear strain as the soil skeleton is disrupted and it is irrecoverable. The relationship of shear modulus with increasing cyclic shear strain amplitude is generally plotted with the normalized vertical axis, G/G_{max} and generally known as the modulus reduction curve. At a very low strain level, the shear modulus can be assumed as maximum shear modulus. Thus, it can be calculated by using simple elastic relationship:

$$G_{max} = \rho \times V_s^2 \quad (2)$$

Where,

ρ = density of the soil, (kg/m^3)
V_s = shear wave velocity, (m/s)

The mass density is often estimated or measured by a nearby subsurface sampling. Hardin & Drnevich [9] listed a few parameters that may affect shear modulus in clean sand including shear strain amplitude, effective stress level and void ratio. For clay, Seed and Idriss [10] summarized that increasing of pore-water pressure will lead to decrement in shear modulus.

IV. Factors affecting Soil Dynamic Properties

Factors that may affect the dynamic properties of soil has been studied and reviewed by numerous researchers. It has been observed that the dynamic properties can be affected by external variables and the intrinsic characteristics of the material [11]. The external variables comprise the confining pressure and loading frequency while the intrinsic characteristics of material are soil type, percentage of fines, soil plasticity and void ratio.

A. *Confining Pressure*

Several studies have been performed to observe the effect of confining pressure on the dynamic behaviours of soil. Kokusho [12] investigated the effect of different confining pressure on dynamic behaviours of dense sand. They found that shear modulus increased proportionally with the increase in confining pressure, but the damping ratio reacted oppositely. These results were supported by GovindaRaju [13] and Tatsuaka et al [14] who performed a similar study. This observation can be explained by the theory established by Winkler and Nur [15] in which the contacts of soil particles and stability are increased and minimize the fluid flow as cracks and pores are filled when subjected to the increased pressure. This phenomenon is known as densification which causes an increase in relative density.

B. *Frequency of Cyclic Loading*

Hardin and Drnevich [9] found that the damping properties of dry sand were not influenced by the applied frequency. Kim et al [16] also discovered that damping effects in dry sand were independent of frequency by using a resonant column and torsional shear device. However, Stoll [17] showed a contrary result when testing on saturated soils. In Stoll [17]'s study, energy dissipation was commenced by the soil skeleton and fluid in pore space when subjected to the low and high frequencies, respectively. GovindaRaju [13] implemented cyclic triaxial tests and found that the frequency of cyclic loading did not significantly affect the shear modulus notwithstanding that significant influence occurred on the damping ratio. In terms of excess pore-water pressure buildup, the rate was increased with the increment in frequency and magnitude of loading.

C. *Void Ratio*

Void ratio of soil will be reduced when subjected to loading or external force. This phenomenon is termed as densification. Densification will increase cyclic strength of soil sample, thus it is an important parameter that influences dynamic properties of soil. Kokusho [12] conducted a series of cyclic triaxial tests and found that the shear modulus increased with the decrease of void ratio.

D. *Soil Plasticity*

Vucetic and Dobry [18] stated that it is the plasticity index of soil rather than void ratio that affected the dynamic properties of soil. This is because plasticity index is usually determined from remoulded soil while void ratio information is obtained from the undisturbed soil. Secondly, plasticity index is dependent on the constituents of soil such as soil mineralogy, particle shape and size while void ratio is dependent on the *OCR*. Since *OCR* has been proven to have no practical effect on the soil dynamic properties, it can be inferred that the influence of void ratio on G/G_{max} ratio and damping ratio could be minimal. The fact that plasticity index and void ratio have the similar influences on the G/G_{max} curve and damping ratio curve was because soils with higher plasticity generally has a larger void ratio.

E. *Percentage of Fines*

Based on researches had done, the percentage of fines in soil will influence the pore pressure response and thus liquefaction behaviour. Seed et al concluded that liquefaction resistance of soil will be influenced only when it comprise more than 5 % of fines of the soil. Furthermore, Hanumantharao and Ramana [19] conducted cyclic triaxial test on sand and sandy silt to examine its damping curves. It was observed that damping ratio decrease albeit increase in silt content as shown in figure x. However the shear modulus is not significant affected.

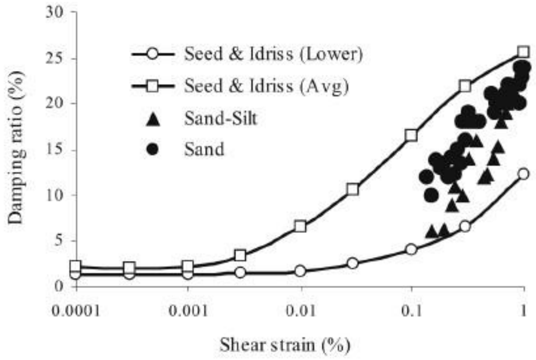

Figure 3. Damping ratio versus shear strain for soils of different fine contents [19]

V. Conclusion

This paper provides an overview of the excellent studies reported by numerous researchers on dynamic properties of soil. Damping ratio and shear modulus are two important dynamic parameters of soil. Confining pressure and frequency of cyclic loading are the main extrinsic factors affecting the dynamic properties of soil, while soil plasticity and percentage of fines are identified as the main intrinsic factors of soil influencing its dynamic behaviours.

From the foregoing reviews, it can be concluded that current studies of soil dynamic properties mainly focus on sandy and clayey soils. Studies of dynamic properties for tropical residual soil that consists of predominantly silty materials are still very limited. It would be interesting to determine how the weathering effect or particle size variations in residual soil affects their dynamic parameters. The results obtained from these experimental works could be useful for performing dynamic analysis of soil-structure interactions in the tropical regions like Malaysia.

Acknowledgment

This study is financially supported by the State Key Laboratory of Geo-hazard Prevention and Geo-environment Protection (Chengdu University of Technology) under Grant No. SKLGP2014K002 and the Ministry of Education Malaysia under Fundamental Research Grant Scheme (FRGS), grant no: 4450/L01.

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About Author:

Dr. LEE Min Lee is an Associate Professor in Universiti Tunku Abdul Rahman, Malaysia. His research interests are in soil dynamic behaviours, slope stability analysis and bio-mediated soil improvement.