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Determination of Small Strain Modulus and Degradation for in-Situ Weathered Rock and Old Alluvium Deposits

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DETERMINATION OF SMALL STRAIN MODULUS AND DEGRADATION FOR IN-SITU WEATHERED ROCK AND OLD ALLUVIUM DEPOSITS

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ABSTRACT

The small strain shear modulus (G_0) and the degradation of shear modulus (G/G_0) with increasing magnitude of shear strain are important soil properties required for the evaluation of site response due to earthquake effects. While these properties are well established for geologically recent alluvial sand and clay materials, published data on the properties of materials derived from in-situ rock weathering and ancient alluvial deposits are limited. This paper presents the results of laboratory testing on completely decomposed granite and tuff in Hong Kong, and weathered Jurong Siltstone and Old Alluvium in Singapore. The small strain shear modulus (G_0) of the materials was determined from bender element tests, while the shear modulus degradation (G/G_0) was assessed from cyclic triaxial test with local strain measurement. The results are compared with the published data of similar materials.

Apart from the laboratory bender element tests, G_0 can also be determined by the in-situ shear wave velocity test. It has been found worldwide that there is generally a reasonable relationship between shear wave velocity and the SPT N value. In this paper, various in-situ shear wave velocity (V_s) testing results obtained from Singapore and Hong Kong have been reviewed and the observed correlations between V_S and SPT N values for various soils are presented.

INTRODUCTION

The evaluation of site response to earthquake ground motions is one of the important parts of earthquake engineering. In site response analyses, several soil properties are required. These include the bulk density of soil, the small strain shear modulus (G_0) and the degradation of shear modulus (G/G_0) with increasing amplitude of shear strain. The bulk density of soil can be determined by standard testing. Small strain shear modulus is related to shear wave velocity that can be measured in laboratory or field testing. The degradation of shear modulus with shear strain can be determined from laboratory testing. While shear modulus degradation curves are well established for recent alluvial sands and clay materials (Seed & Idriss 1970, Stokoe & Lodde 1978 , Sun et al. 1988, Vucetic and Dobry 1991), there is a potential requirement for a better understanding of the shear modulus degradation curves of weathered rock and ancient alluvial deposits. In this study, cyclic triaxial tests with shear wave velocity measurement were carried out to obtain the shear modulus degradation curve of decomposed granite and tuff in Hong Kong, and weathered Jurong Siltstone and Old Alluvium in Singapore. The results are presented and discussed in this paper.

It has been found worldwide that shear wave velocity can be reasonably correlated to the SPT N value. As part of this process the relationships between SPT N value and shear wave velocity have been studied for typical soils in Hong Kong and Singapore. The established correlation relationships for these materials are presented in this paper.

GEOLOGICAL CONDITION

The main rock types in Hong Kong are Mesozoic volcanic and plutonic rocks. The two rock types cover about 85% of rock outcrop on land (GE0 2009). A simplified geological map of Hong Kong (GE0 2009) is shown in Fig. 1. The warm and humid subtropical climates of Hong Kong promoted rock weathering by chemical alteration processes (Irfan 1996). The state of decomposition of igneous rocks in Hong Kong is commonly classified by a six-fold material decomposition grade scheme (Grade I to Grade VI), with the degree of decomposition increases from Grade I to Grade VI. A general description of the characteristics of each material decomposition grade is given in GEO (1988).

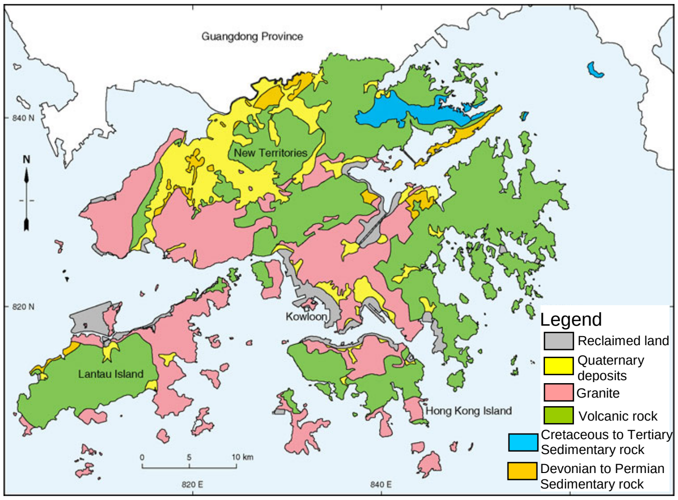

Fig. 1. Simplified Geological Map of Hong Kong (GEO 2009)

The geological map of Singapore (Public Works Department, Singapore 1976) is presented in Fig. 2. Singapore is underlain by sedimentary rocks, decomposed granite and Old Alluvium where in many areas lies beneath soft soils comprising peats, sands and soft marine clays up to 50m below the ground level. At the south and southwest of Singapore, bedrock comprises mainly stratified sedimentary rocks of the Jurong siltstone formation. Weathering has reduced some of the sandstone with occasional mudstones beds to loose clayey silty sand. The highly weathered sedimentary rock mainly comprises hard clayey silt. Old Alluvium exists at the east and northwest of Singapore. The material mainly comprises dense cemented sand and stiff silty clay. The Old Alluvium normally has high SPT N value greater than 20 and undrained shear strength greater than 35kPa.

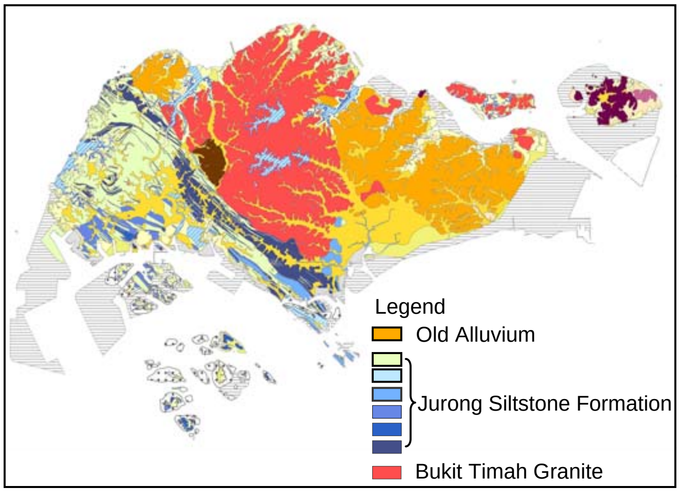

Fig. 2. Geological Map of Singapore (Public Works Department, Singapore 1976)

TESTING MATERIALS

Mazier samples of completely decomposed granite (CDG; Grade V) and completely decomposed volcanic tuff (CDV; Grade V) from Hong Kong, Old Alluvium (OA) and decomposed siltstone of the Jurong formation from Singapore, were tested. The details of the soil specimens are summarised in Table 1.

Table 1. Details of Soil Specimens

Material	**Description**	**Bulk density, ρ (kg/m^3)**	**Plasticity Index, PI (%)**
Completely decomposed granite (CDG)	Stiff, yellowish brown, silty SAND	1950	-
Completely decomposed volcanic tuff (CDV)	Stiff, yellowish brown, clayey SILT	2000	14
Old Alluvium (clay)	Stiff, light gray with mottled brown silty CLAY	2000	32
Old Alluvium (gravelly sand)	Very dense, light yellowish gray, fine grained SAND	2100	-
Old Alluvium (cemented sand)	Very dense, light yellowish gray, fine grained cemented SAND	2100	-
Decomposed siltstone	Very stiff, light gray with mottled purple silty CLAY	2000	23

EQUIPMENT AND TEST PROCEDURE

The cyclic triaxial testing equipment is shown in Fig. 3. It comprises a computer-controlled triaxial testing system equipped with bender elements to determine the shear modulus of soil at very small strains (G_0). Hall effect transducers were mounted on the specimen to measure the local axial and radial strains. A mid-plane pore pressure probe was installed to measure the excess pore water pressure of the specimen during cyclic loading.

Back pressure saturation was first carried out on the specimens at the estimated in situ effective stress state (mean effective stress (p') = deviatoric stress (q) = 80kPa). Once full saturation was achieved, the shear wave velocity of the specimen (v_s) was measured. Stress-controlled constant p' cyclic test of 5 cycles at a particular stress amplitude was performed. The mean value of q was kept constant during the cyclic test. The cycling test continued with an increased value of the cyclic component, such that the amplitude of shear strain increased from about 0.01% to 0.2 – 0.4%. A mid-plane pore pressure probe was used to monitor the excess pore water pressure at the mid-height of the specimen during cyclic loading. The excess pore water pressure at the mid-height of the specimen should not exceed 10% of the current mean effective stress, p'. The period of each cycle is 30s (frequency = 0.03Hz). For some cycles with large cyclic component, the period was extended to avoid building up of large excess pore water pressure. After completing the set of cyclic loading, the specimens were loaded to p' = q = 160kPa and 400kPa, and the procedures described above were repeated at these stress states.

Fig. 3. Triaxial Testing Equipment (Ng and Leung 2007)

EXPERIMENTAL RESULTS

The results of shear wave velocity measurement using bender elements are summarised in Table 2.

The results of cyclic triaxial test on CDG and CDV are shown in Fig. 4. The shear modulus of the materials determined in the cyclic triaxial tests is normalized by the shear modulus at very small strains (G_0) obtained from shear wave velocity measurement. The rates of shear modulus degradation of CDG and CDV are similar. Schnaid et al. (2000) present plots of shear modulus versus shear strain, for granitic saprolites (CDG) and the data are also shown in Fig. 4 for comparison. The test results of CDG and CDV agree well with the results from Schnaid et al. (2000). A shear modulus degradation curve for CDG and CDV is proposed and shown in Fig. 4.

Table 2. Results of Shear Wave Velocity Measurement

Material	**Mean Effective Stress, p′ (kPa)**	**Shear Modulus, G_0 (MPa)**
Completely decomposed granite (CDG)	80	54
	160	87
	400	148
Completely decomposed volcanic tuff (CDV)	80	59
	160	81
	400	124
Old Alluvium (clay)	80	30
	160	46
	400	72
Old Alluvium (gravelly sand)	80	210
	160	306
	400	486
Old Alluvium (cemented sand)	80	79
	160	120
	400	200
Decomposed siltstone	80	113
	160	151
	400	209

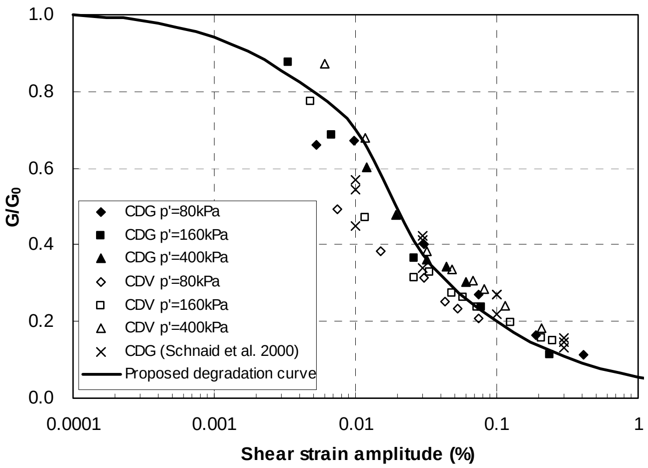

Fig. 4. Normalized Shear Modulus (G/G_0) of CDG and CDV vs. Shear Strain

The degradation of the normalized shear modulus (G/G_0) of decomposed siltstone with increasing shear strain amplitude is shown in Fig. 5. The degradation curve proposed for CDG and CDV is also shown in the figure for comparison. The decomposed siltstone shows a lower shear modulus degradation rate compared with CDG and CDV. A shear modulus degradation curve for decomposed siltstone is proposed and shown in Fig. 5.

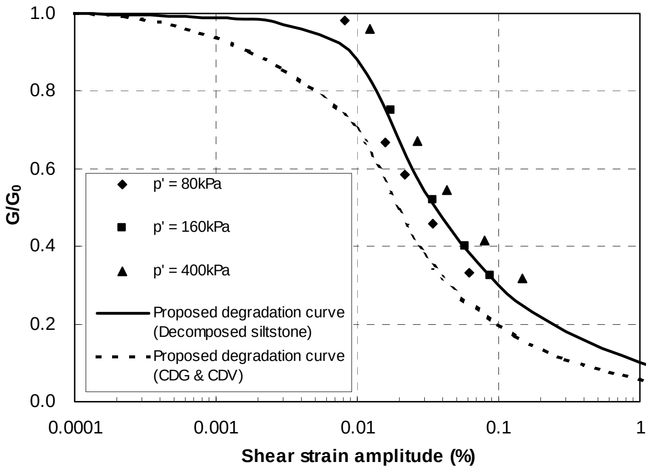

Fig. 5. Normalized Shear Modulus (G/G_0) of Decomposed Siltstone vs. Shear Strain

The results of cyclic triaxial test on Old Alluvium (clay) are shown in Fig. 6. The material shows a shear modulus degradation rate close to the curve presented by Stokoe & Lodde (1978) and corresponds to the clay curves from Vucetic and Dobry (1991) and Sun et al. (1988) for soils with PI of 15%.

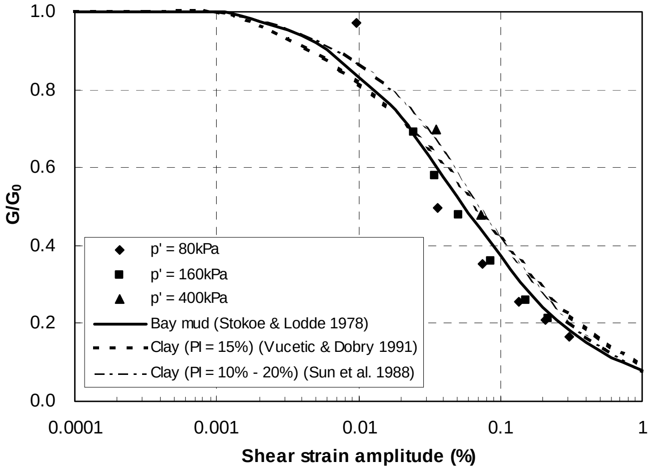

Fig. 6. Normalized Shear Modulus (G/G_0) of Old Alluvium (Clay) vs. Shear Strain

The test results of Old Alluvium (gravelly sand and cemented sand) are shown in Fig. 7. The gravelly sand, with less fines content compared with cemented sand, shows a higher shear modulus degradation rate. The proposed shear modulus degradation curve for Old Alluvium (gravelly sand) is shown in the figure. The Old Alluvium (cemented sand) shows a shear modulus degradation rate close to the mean curve for sand proposed by Seed & Idriss (1970).

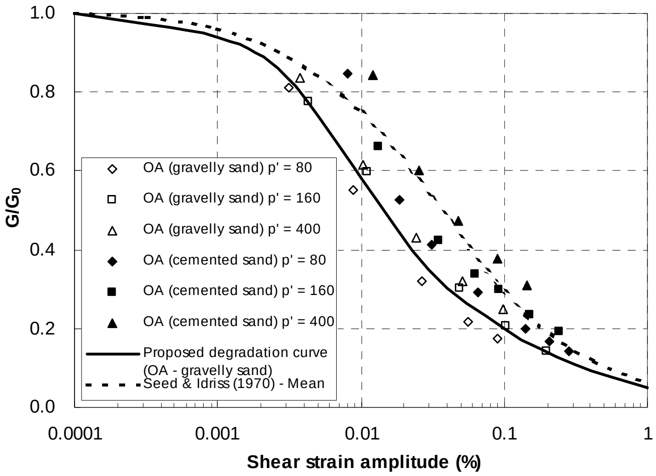

Fig. 7. Normalized Shear Modulus (G/G_0) of Old Alluvium (Gravelly Sand and Cemented Sand) vs. Shear Strain

The above shear modulus degradation curves for weathered materials and Old Alluvium determined in cyclic triaxial tests were adopted in the evaluation of site response due to earthquake ground motions.

IN-SITU SHEAR WAVE VELOCITY MEASUREMENT

As part of a seismic study, site-specific soil response analysis is required to calculate soil amplification factors. To establish a small strain stiffness soil model, it is necessary to determine the shear wave velocity, V_s, of all soil types to correlate to the small strain shear modulus as shown in the following equation:

$$G_0 = \rho V_s^2 \qquad (1)$$

where ρ is bulk density in kg/m^3.

The shear wave velocity of different soil types can be measured by the in-situ shear wave velocity test which is not commonly carried out in the ground investigation work. Alternatively, V_s can be determined approximately from the correlations between SPT N values and shear wave velocity if such in-situ test is not available. The available published SPT N values and shear wave velocity test results in Hong Kong (Arup 1998; Chan and Bell 2000; EGS 1998, 2001; Europeene de Geophysique 2003; Halcrow 1999; Kwong 1998; Lee et al. 1998; Ng and Leung 2007; Shum 2003; Tam 2002; Wong et al. 1998, 2000) and Singapore (Veijayaratnam et al. 1993) has been used to generate a suite of correlation relationships between SPT N value and shear wave velocity.

The available shear wave velocity measurements were carried out using the following techniques:

- Crosshole;
- Downhole, both within boreholes and by seismic cone;
- Suspension PS Logging;
- Refraction;
- Spectral Analysis of Surface Waves; and
- Continuous Surface Waves.

The correlation relationships between SPT N value and shear wave velocity for fill, marine deposits (silt/clay), alluvium deposits (silt/clay), alluvium deposits (sand), completely weathered sedimentary rock, and completely weathered granite are shown in Figs. 8 to 12. By least square analysis, a series of correlation relationships have been derived based on the shear wave velocity data obtained from various sites. These correlation relationships have been developed to estimate the mean value of shear wave velocity for different materials. It can be seen from the figures that there are distinct tendencies for different soil types. The correlation relationships generally have a large scatter. The scatter can be attributed to both the inherent variability of the materials and the variation in the results from different shear wave velocity measurement and SPT techniques.

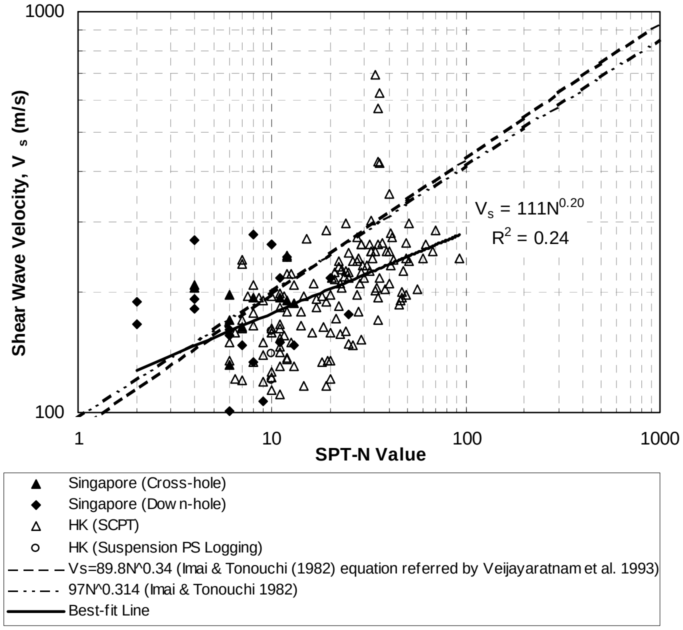

Fig. 8. Correlation Relationship between SPT N Value and Shear Wave Velocity for Fill (Sand and Silt)

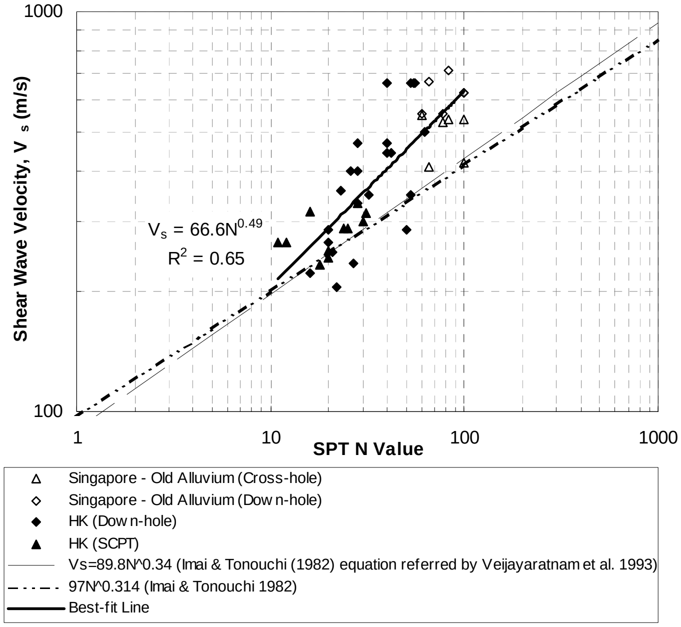

Fig. 9. Correlation Relationship between SPT N Value and Shear Wave Velocity for Alluvium (Sand)

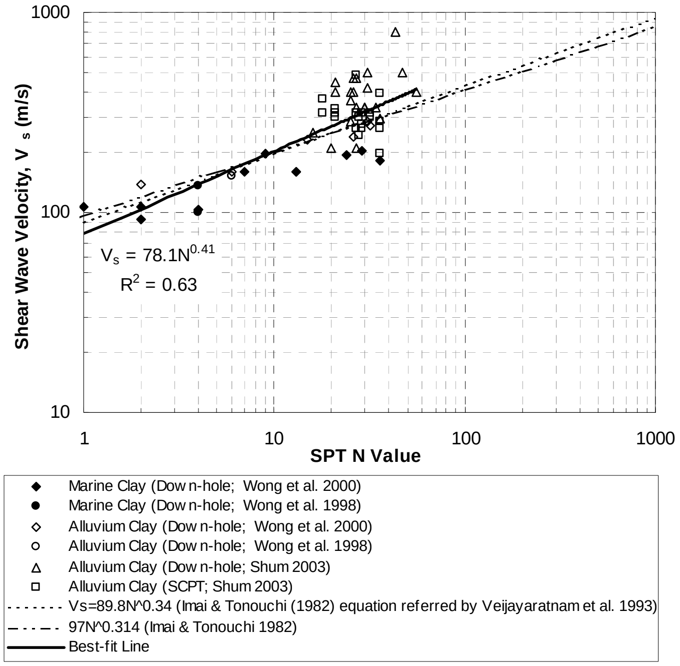

Fig. 10. Correlation Relationship between SPT N Value and Shear Wave Velocity for Alluvium and Marine Clay

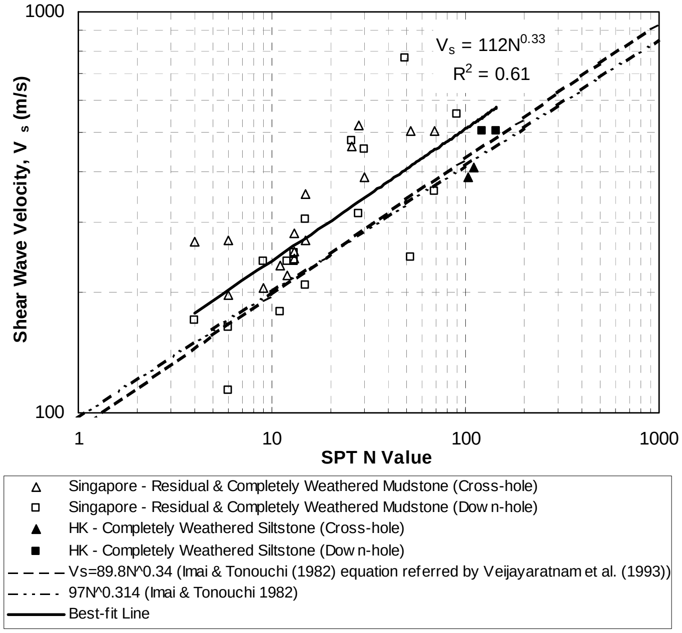

Fig. 11. Correlation Relationship between SPT N Value and Shear Wave Velocity for Completely Weathered Sedimentary Rock

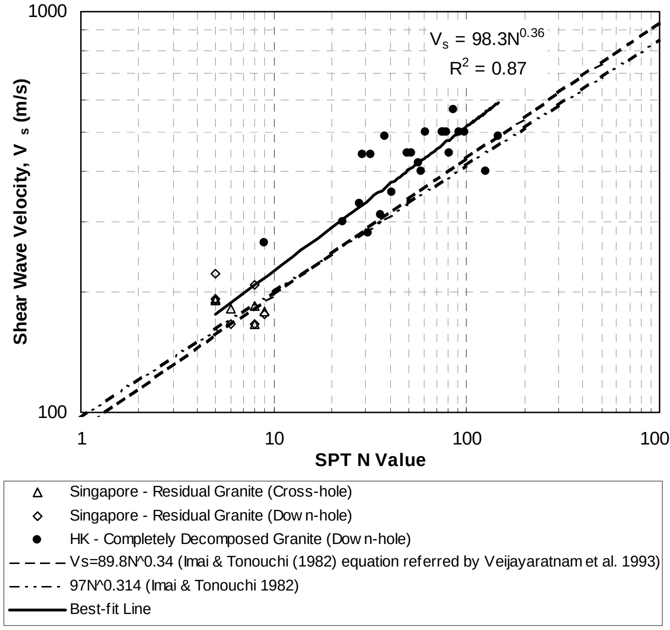

Fig. 12. Correlation Relationship between SPT N Value and Shear Wave Velocity for Completely Decomposed Granite

CONCLUSIONS

The small strain shear modulus and the degradation of shear modulus with shear strain are the important soil parameters for the evaluation of site response to earthquake ground motions. While these parameters are well established for recent alluvial sands and clay materials, there is a potential requirement for a better understanding of the parameters for weathered rock and ancient alluvial deposits. Cyclic triaxial tests with shear wave velocity measurement were carried out to determine the small strain shear modulus and the shear modulus degradation curve of decomposed granite and tuff in Hong Kong, and weathered Jurong Siltstone and Old Alluvium in Singapore. The results are presented in this paper and compared with published results for sand and clay. In addition, the observed relationships between shear wave velocity and SPT N value for typical soils in Hong Kong and Singapore are presented. The established relationships can be used to estimate the shear wave velocity when the in-situ shear wave velocity test is not available.

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