

A study of shear wave velocity correlations of Bangkok subsoil

Estudio de correlaciones de la velocidad de onda de corte para el subsuelo de Bangkok

Fecha de entrega: : 25 de Febrero 2010

Fecha de aceptación: 20 de Mayo 2010

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One of the essential soil dynamic parameters, especially in geotechnical earthquake engineering applications, is the shear wave velocity. The shear wave velocity can be used to estimate the low strain amplitude shear modulus which is one of the input parameters for a seismic site response analysis. There were a few investigation schemes trying to determine the shear wave velocity of Bangkok Clay from both laboratory and field tests. Two recent studies on the shear wave velocity of Bangkok Clay have been published by Teachavorasinskun and Lukkunaprasit (2004) and Seng (2009). The former presented a simple correlation for shear wave velocity of Bangkok clays which assume that the shear wave velocities are linear functions with depth for four particular sites around Bangkok. The latter conducted a series of down-hole tests and multi-channel analysis of surface wave (MASW) to direct measure the shear wave velocity profiles of three particular sites in Bangkok. This paper presents a unified correlation of shear wave velocity for Bangkok subsoil based on previous studies and two recent studies.

Keywords: shear wave velocity, small strain shear modulus, down hole test, multi-channel analysis of surface wave, Bangkok clay

La velocidad de onda de corte es uno de los parámetros esenciales en dinámica de suelos, especialmente en aplicaciones de ingeniería geotécnica sísmica. La velocidad de onda de corte puede ser usada para estimar el módulo de corte para bajas amplitudes de deformación. Este módulo es uno de los parámetros de entrada en análisis de respuesta sísmica de sitio. Han habido algunos proyectos de investigación que han tratado de determinar las velocidades de onda de corte de la arcilla de Bangkok a partir de ensayos de laboratorio y de terreno. Dos estudios recientes sobre la velocidad de onda de corte de la arcilla de Bangkok han sido publicados por Teachsvorasinskun y Lukkunaprasit (2004) y Seng (2009). El primero presenta una correlación simple para la velocidad de onda de corte de las arcillas de Bangkok. Se asume que la velocidad de onda de corte es una función lineal de la profundidad para cuatro sitios alrededor de Bangkok. El segundo presenta resultados de una serie de ensayos down hole y análisis multicanal de ondas de superficie para medir directamente perfiles de velocidad de ondas de corte en tres sitios de Bangkok. Este artículo presenta una correlación unificada de la velocidad de onda de corte para el subsuelo de Bangkok basado en estudios previos y dos estudios más recientes

Palabras clave: velocidad de onda de corte, módulo de corte de pequeñas deformaciones, ensayo down hole, análisis multi-canal de ondas de superficie, arcilla de Bangkok

Introduction

Earthquake occurrence causes an energy release which moves as a shock front or strain pulse through the earth. This energy propagates outward in the form of seismic waves such as primary or compression waves (P wave) and shear or transverse waves (S wave). Shear waves are recognised as a motion of the soil particles in a direction perpendicular to the direction of propagation of the wave. The velocity

of a shear wave (V_s) which travels through the earth can be expressed in terms of the elastic modulus and material density as follows:

$$V_s = \sqrt{\frac{G}{\rho}} \quad (1)$$

where G is the dynamic shear modulus and ρ is the material bulk density. The soil shear wave velocity can then be used to estimate the low strain amplitude shear modulus which is an important parameter in building codes for

seismic design (NEHRP, 1997). The shear modulus has its maximum at small strains and decreases with increasing shear strain.

The earthquake engineering community widely uses the shear wave velocity in design applications (Kramer, 1996). The shear wave velocity can be obtained from laboratory and field tests. The cross-hole and down-hole methods have become the standard techniques for dynamic testing to determine the in-situ shear wave velocity. A polarized shear wave is generated in one borehole (or at the surface) and the time is measured for the shear wave to travel a known distance to the geophone in the borehole. However, these geophysics tests are still limited. Some empirical correlations with SPT and CPT are recommended to estimate the shear wave velocity.

A rough correlation between the number of blows per foot in standard penetration tests and the velocity of shear waves is shown in Figure 1. Imai and Tonouchi (1982) proposed empirical correlation equations between V_s in m/s and $(N_1)_{60}$ values as:

For alluvial clay:

$$V_s = 100[(N_1)_{60}]^{1/3} \quad (2)$$

For alluvial sand:

$$V_s = 80[(N_1)_{60}]^{1/3} \quad (3)$$

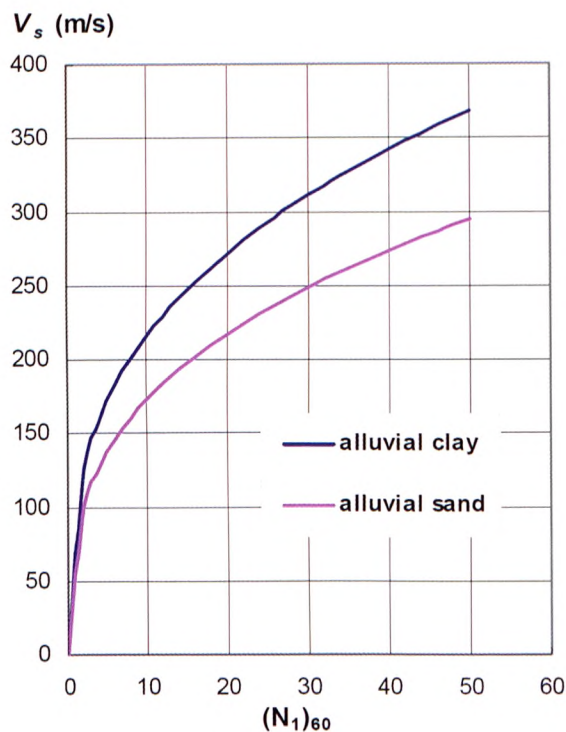


Figure 1: Empirical relation between the shear wave velocity and $(N_1)_{60}$, (after Imai and Tonouchi, 1982)

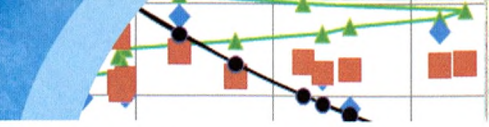
A number of factors affecting the measured blows per foot such as energy ratio, sampler type and rod length need to be considered for using $(N_1)_{60}$ values to estimate engineering properties. This is known as the corrected or standard SPT number of blows per foot. The correction scheme suggested by Skempton (1986) is employed in this study. In Thailand the Donut hammer type is commonly employed, which has an energy efficiency in the range of 50 to 55%.

Shear wave velocity measurements in Bangkok subsoil

Bangkok, the capital city of Thailand, is situated on a large and extremely flat plain, commonly known as the “lower Central plain” of Thailand. The length from north to south of the plain is about 250 km and the average width is approximately 200 km. The top of Bangkok subsoil is generally covered with a very soft clay. Under the soft deposit there are layers of stiff to hard clays and dense sands up to the base rock. The lower Central plain consists of a broad deep basin filled with alluvial and deltaic sediments with occasional shallow sea sedimentation. The bedrock depth is estimated to be between 550 and 2000 m. The uppermost soil layer is “soft” silty marine clay, usually referred to as “soft Bangkok clay”. The soil deposit underlying the whole Bangkok and its surrounding areas consist of nearly uniform and horizontal layers of clay and sand. The typical soil profile in Bangkok area can be summarised in Table 1 (Shibuya *et al.*, 2003).

Table 1. Typical Bangkok subsoil (Shibuya *et al.*, 2003)

Depth, m	Description
0 to 14	Bangkok Soft Clay – dark grey highly compressible soft clay with 2 m weathered zone forming a hard crust
14 to 25	First Stiff Clay – light grey and brown fissured stiff clay
25 to 40	First Sand layer – dense alluvial non-uniform sand, occasionally inter-bedded with stiff clay. Classified in parts as clayey sand.
40 to 44	Second Stiff Clay – light grey and brown, stiff often fissured silty clay
44 to >70	Second Sand layer - clean light grey silty sand



Many researchers have investigated the shear wave velocity profiles for soft Bangkok clays using different methods. From a comprehensive investigation of soil characteristics at nine different sites around the Bangkok metropolitan area, Ashford *et al.* (1996) developed a generalised soil profile and a corresponding generalised shear wave velocity profile as shown in Figure 2. They first estimated shear wave velocity (V_s) from specific field and laboratory data of the nine sites using several published empirical correlations, and then confirmed such estimates with actual in-situ V_s measurements at another four sites around Bangkok using the down-hole method. The obtained generalised V_s profile shows extremely low values of V_s in soft Bangkok clay (about 60 to 100 m/s). The velocity increases sharply and considerably to about 200 to 250 m/s in the first stiff clay, and it continues increasing at a slower rate in the deeper strata. Ashford *et al.* proposed an empirical correlation between shear wave velocity, V_s in m/s and the undrained shear strength, s_u in kPa for Bangkok soft clay as :

$$V_s = 23s_u^{0.475} \quad (4)$$

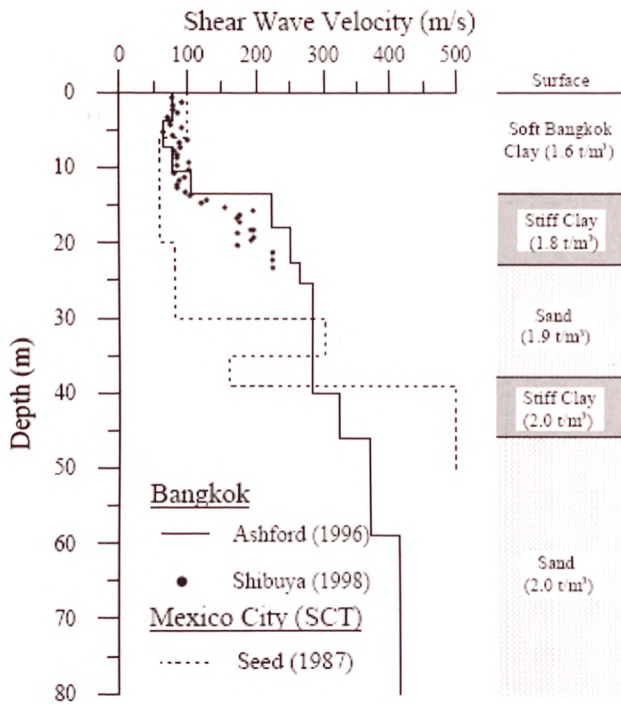


Figure 2. Generalised Bangkok soil and shear wave velocity profiles (Warnitchai *et. al.*, 2000)

Teachavorasinskun and Lukkunaprasit (2004) have re-analysed the down-hole seismic test results from Shibuya *et al.* (2003) and Ashford *et al.* (1996) to explore the shear wave velocity profiles in four sites around Bangkok. They found that the shear wave velocity of the

top 30 m V_s (in m/s) could be linearly correlated to the depth z (in m) from the ground surface as:

For Chulalongkorn University site:

$$V_s = 45.4 + 8.8z \quad (5)$$

For Asian Institute of Technology (AIT) site:

$$V_s = 45.1 + 8.32z \quad (6)$$

For Suvarnabhumi airport site:

$$V_s = 63.7 + 3.5z \quad (7)$$

For Lad Kra Bang site:

$$V_s = 50 + 3.3z \quad (8)$$

Recently, the shear wave velocity profiles of Bangkok subsoil have been investigated using multi-channel analysis of surface wave method (MASWM) and down-hole test. The MASWM is a non-destructive test, from which shear wave velocities can be obtained via an inversion technique. Seng (2009) investigated the shear wave velocity profiles of subsoil at seven different locations in Thailand including four sites in Bangkok metropolitan area within 30 m depth by MASWM technique. Palasri and Ruangrassamee (2009) have also conducted seismic down-hole tests and determined shear wave velocities in three boreholes at depths of 30 m to 37 m in Bangkok area.

Typical Bangkok boring log data

In this study, three sites in Bangkok area which are Chulalongkorn University (CU), Asian Institute of Technology (AIT), and Thailand Meteorological Department (TMD) have been selected. The summarised soil descriptions with the undrained shear strength (s_u) for these sites are presented in Table 2. The determination of s_u values for the top 15 m are from unconfined compression tests (UC); on the other hand, s_u values for the deeper soil can be obtained from correlations of the $(N_1)_{60}$ value as suggested by the following relations.

Terzaghi and Peck (1967) suggested the empirical correlation between the undrained shear strength s_u and $(N_1)_{60}$ value for sandy clays as:

$$\frac{s_u}{p_a} = 0.06 (N_1)_{60} \quad (9)$$

where p_a is the atmospheric pressure (≈ 100 kPa).

Sambhandharaksa and Taesiri (1987) investigated the relations of undrained shear strength s_u (in kPa) with SPT-N value for Bangkok clay and suggested the empirical

correlations as following.

For CH:

$$s_u = 5.20(N_1)_{60} \quad (10)$$

For CL:

$$s_u = 6.82(N_1)_{60} \quad (11)$$

Table 2: Boring log reports at three studied sites

Depth (m)	CU			AIT			TMD (Bangna)		
	s_u (kPa)	SPT. N	Type	s_u (kPa)	SPT. N	Type	s_u (kPa)	SPT. N	Type
0.5			CH	23.30		CH	34.40		CH
1.5	12.5		CH	23.30		CH	34.40		CH
2.5	13.7		CH	30.11		CH	31.88		CH
3.5	16.3		CH	35.54		CH	27.31		CH
4.5	23.0		CH	23.74		CH	18.84		CH
5.5	22.7		CH	17.77		CH	14.15		CH
6.5	20.0		CH	13.87		CH	12.47		CH
7.5	20.0		CH	8.20		CH SC	16.34		CH
8.5	24.7		CH	21.29		CH	21.28		CH
9.5	31.0		CH	42.04		CH	27.21		CH
10.5	36.0		CH	61.24		CL	35.27		CH
11.5	78.3		CL		17.8	CL	40.97		CH
12.5		12	CL		17.1	CL	41.33		CH
13.5		12.7	CL		17.8	CL	34.46		CH
14.5		13.9	CL		15.7	CL	40.94		CH
15.5		15.4	CL		14.6	CL	50.70	19	CH
16.5		17.4	CL		22.6	CL		20.4	CH
17.5		18.5	CL		33.9	CL		17.7	CH
18.5		19.1	CL		49.2	SM		15.1	CH
19.5		19.8	CL		75.5	SM		20.4	ML SM
20.5		26.5	CL		71.4	SM		28.1	CL
21.5		33.5	CL		56.8	SP-SM		40.3	CL
22.5		30.8	CL		52.3	SP-SM		67	SM
23.5		31.9	CL		38.4	SP-SM		64.7	SM
24.5		33.5	CL		23.7	CL		51.1	SM
25.5		30.8	CL		22.4	CL		41.8	SM
26.5		41.7	CL		23.4	CL		36.7	SM
27.5		54.5	SM		22.9	CL SC		31.7	SM
28.5		51.8	SM		12.2	CL SC		20.4	CH
29.5		38.4	SM		12.7	SC CL		15.6	CH
30.5		26.1	SM		17	SC CL		16.1	CH
31.5		36.8	SM					26.8	CH
32.5		49.3	SM					27.2	CH
33.5								26.9	CH
34.5								41.6	CH
35.5								41.8	CH
36.5								40.8	CH

The undrained shear strength variation with depth for the three sites studied are shown in Figures 3, 4 and 5. The value of s_u for the top 11 m soil at CU and AIT sites, and for the top 15 m soil at TMD site are determined from the unconfined compressive strength q_u value, i.e. $s_u = q_u/2$. Under the top soil layer from which undisturbed samples cannot be collected, s_u values are estimated using the empirical correlation in equation (9) for sandy clay (Terzaghi and Peck, 1967) and in equations (10) and (11) for clayed soils (Sambhandharaksa and Taesiri 1987).

Correlation of shear wave velocity V_s with undrained shear strength s_u

A number of studies have proposed an empirical correlation for the shear wave velocity of Bangkok subsoil as a power function of the undrained shear strength

(Ashford *et al.*, 1996), as linear function of the soil layer depth (Teachavorasinskun and Lukkunaprasit, 2004) and as a correlation with the $(N_1)_{60}$ values (Palasri and Ruangrassamee, 2009). Due to the different local site conditions in Bangkok metropolitan area, and in order to evaluate the seismic site response for the whole Bangkok subsoil, suitable empirical correlations for the shear wave velocity of Bangkok subsoil should be developed.

Comparisons of the shear wave velocity prediction from previous studies with the V_s data from down-hole and MASW methods are presented in Figures 6, 7 and 8. The empirical correlations are considered to follow and verify the shear wave velocity profiles determined by seismic down-hole tests and the MASW method. Therefore, the correlations of shear wave velocity V_s (in m/s) with the normalised undrained shear strength parameter (s_u/p_a), are proposed in this study based on a regression analysis. The equations can be expressed as in equations (12) and (13) for the shear wave velocity from the down-hole and the MASW methods respectively and they are also illustrated in Figure 9.

$$V_s = 187.42 \left(\frac{s_u}{p_a} \right)^{0.372} \quad (12)$$

$$V_s = 227.93 \left(\frac{s_u}{p_a} \right)^{0.510} \quad (13)$$

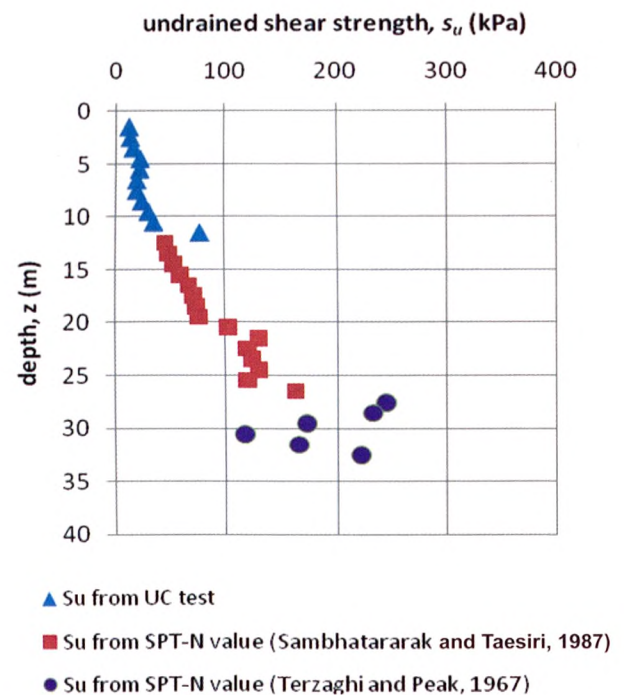


Figure 3: Undrained shear strength s_u versus depth z at Chulalongkorn University (CU) site

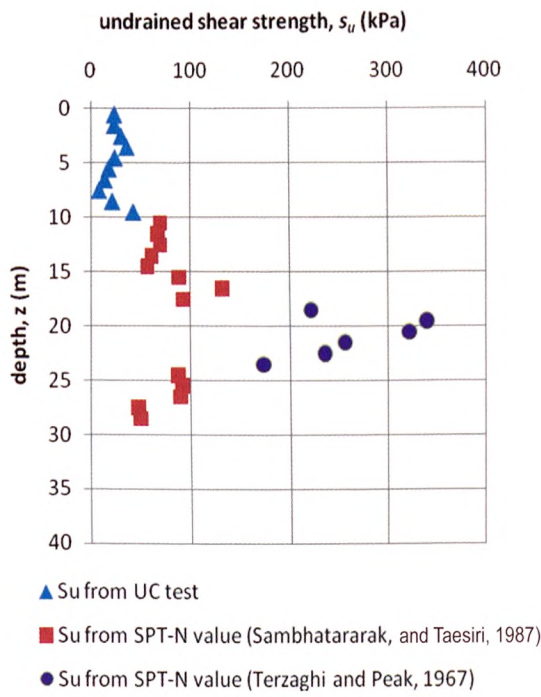


Figure 4: Undrained shear strength s_u versus depth z at Asian Institute of Technology (AIT) site

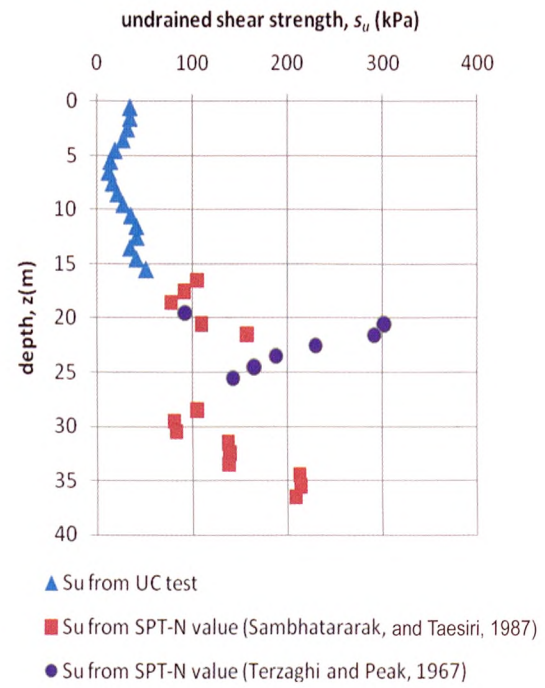


Figure 5: Undrained shear strength s_u versus depth z at Thailand Meteorological Department (TMD) site

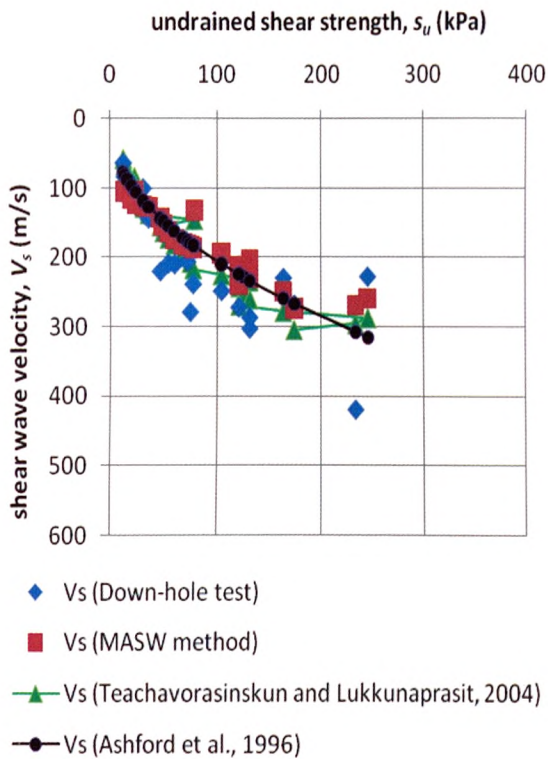


Figure 6: Shear wave velocity V_s versus undrained shear strength s_u at Chulalongkorn University (CU) site

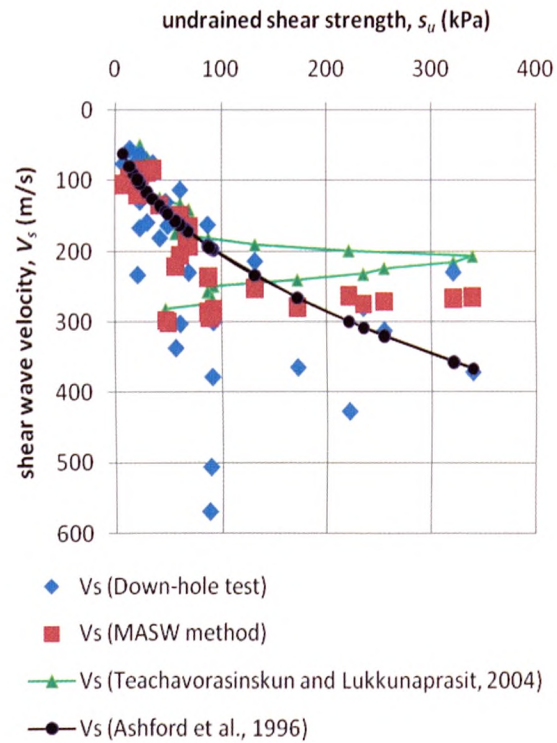


Figure 7: Shear wave velocity V_s versus undrained shear strength s_u at Asian Institute of Technology (AIT) site

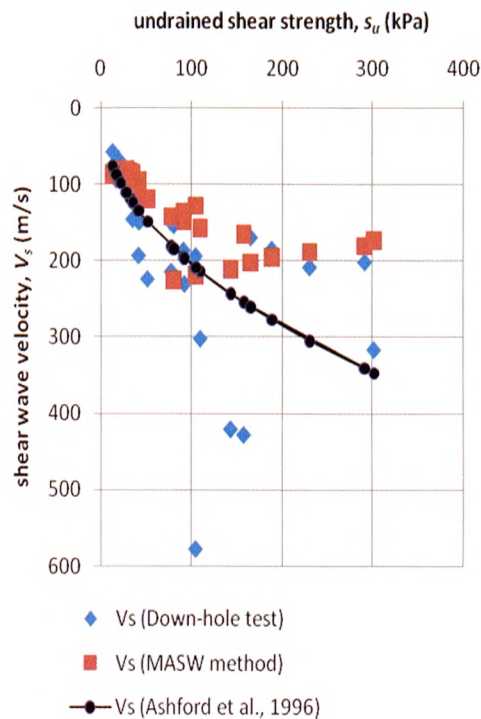


Figure 8: Shear wave velocity V_s versus undrained shear strength s_u at Thailand Meteorological Department (TMD) site

Discussions and conclusions

There are many empirical formulas trying to correlate the shear wave velocity (V_s) with some soil parameters such as depth of soil layers (z), SPT-N value and undrained shear strength of soil (s_u). The soil profiles generally vary depending on the geological condition of each location; on the other hand, the SPT blow-count (N -value) is an empirical parameter linking the soil strength and stiffness. Among them, the undrained shear strength (s_u) is one of the theoretical soil parameter which is simply evaluated from many laboratory and field tests. The proposed correlations therefore represent a relationship between the shear wave velocity and the undrained shear strength. A new series of down-hole tests (Palasri and Ruangrassamee, 2009) and multi-channel analysis of surface wave method (Seng, 2009) of three particular sites in Bangkok are combined with previous studies by Ashford *et al.* (1996), Shibuya *et al.* (1999), and Teachavorasinskun and Lukkunaprasit (2004) to confirm the results of the shear wave velocity measurements of Bangkok subsoil.

This study is intended to investigate the shear wave velocities of Bangkok subsoil for seismic site response analysis. This paper therefore presents a unified correlation

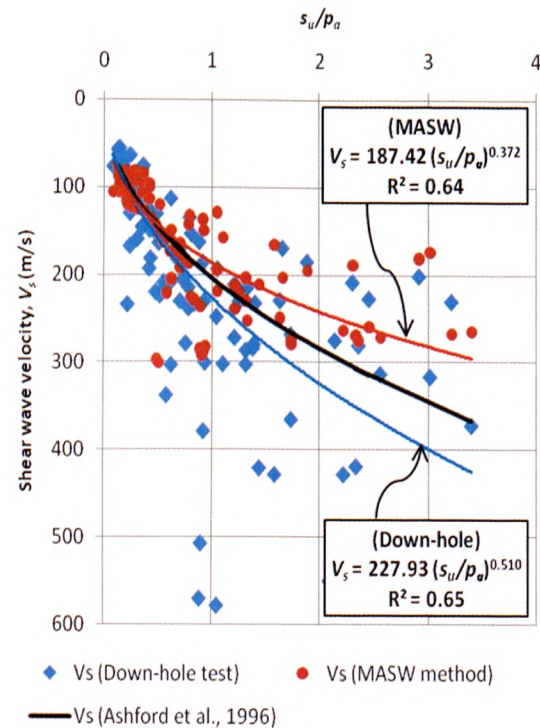


Figure 9: Shear wave velocity profile of Bangkok subsoil

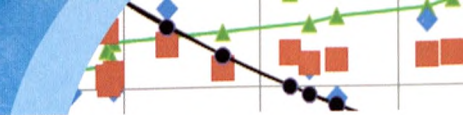
of shear wave velocity for Bangkok subsoil based on previous studies and also on two recent studies. As shown in Figure 9, the interpretation of correlation equations (12) and (13) are suggested by combining the shear wave velocity values from three selected sites in the Bangkok area. In comparison with previous studies, it is found that the correlations suggested by Ashford *et al.* (1996) is located in between the results from MASW method and down-hole tests. The correlation based on down-hole tests offers a higher shear wave velocity prediction than the correlation from MASW method. It should be also noted that the correlations proposed in this study for Bangkok subsoil are limited to undrained shear strengths up to 300 kPa (approximately 30 m depth).

Acknowledgement

This work was supported by the Thailand International Development Cooperation Agency (TICA). This funding is gratefully acknowledged.

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