COMPARISON OF ESTIMATED AND MEASURED V_S PROFILE FOR BANGKOK, THAILAND

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ABSTRACT

A comparison of estimated and measured low-strain shear wave velocity (V_s) Bangkok soils is presented, along with a discussion of the potential impact of the extremely low observed velocities. Data from over 44 soil borings around the greater Bangkok Metropolitan Area were used with 9 existing V_s correlations. Based on the results, a best-estimate shear wave velocity profile was developed for Bangkok to 80m depth. Downhole V_s testing was then conducted to confirm the estimated profiles. The agreement between the estimated and measured velocities was good, especially considering all correlations were based on soils from other countries. These first ever in situ velocity measurements in Bangkok show alarmingly low values in the soft Bangkok clay (as low as 60 m/s). These velocities are comparable to measured values in San Francisco and Mexico City, and will have significant impact on quantifying seismic hazards facing the city. In addition, though in situ testing is preferred, the study confirms that existing correlations can yield quite reasonable estimates of V_s and shear modulus, when typical soil boring information is available.

INTRODUCTION

Thailand, and Bangkok in particular, has historically been considered by most people as areas of low seismicity. This is evidenced by the fact that Thailand currently has no seismic provisions in its building code. However, a recent series of moderate earthquakes in Thailand, some of which causing damage (e.g. 11 September 1994 Phan Earthquake), and the highly publicized destruction resulting from the 1995 Hyogoken-Nambu Earthquake have served as a wake-up call to the people of Thailand, nearly 10 million of whom live in the nation's capital city of Bangkok. The city is located near the Gulf of Thailand in the Lower Central Plain, and lies upon deep alluvial sediments. The uppermost of these sediments is referred to as *soft Bangkok clay*, and has characteristics similar to other soft clay found elsewhere in the world, such as San Francisco Bay Mud, and presumably has the ability to amplify earthquake ground motions. The potential seismic hazards facing Thailand still need to be assessed, and though Bangkok is a considerable distance from any known active fault, the fate of Mexico City in the 1985 Michoacan Earthquake is often referenced. Bangkok lies only some 400 kilometers away from seismic source zones capable of magnitude 7+ earthquakes. Though the regional seismicity is much lower than the western coast of Mexico, the deep alluvial sediments and soft clay underlying Bangkok, combined with the lack of seismic provisions in the building code, clearly demonstrate the need to begin to quantify the risk facing the city of 10 million people.

One of the key elements in addressing the seismic hazard is to characterize the soil underlying Bangkok for seismic site response analysis, namely: developing a shear wave velocity (V_s) profile in order to obtain the low-strain shear modulus. Since no previous in situ V_s measurements had been made in Bangkok, the initial phases of this study focused on the use of published correlations from elsewhere to develop a best-estimate V_s profile. Though use of correlations alone is generally discouraged, it is often the only alternative, especially in developing countries where funding is extremely limited. However, funding was subsequently obtained to conduct the first ever in situ shear wave velocity testing of Bangkok subsoils. This paper presents a comparison of the estimated and measured V_s profile, and discusses the potential impact of the data on the evaluation of the seismic hazard facing Thailand.

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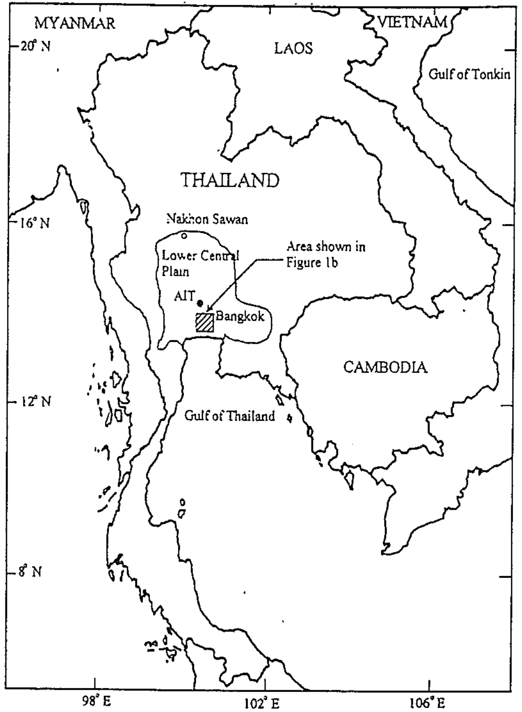

Fig. 1a Map Showing Thailand's Lower Central Plain (a), as well as the Location of Data Collection Sites and In Situ Testing Sites (a and b)

DEVELOPMENT OF GENERALIZED SOIL PROFILE

Bangkok lies within the 50,000 km^2 Lower Central Plain of Thailand as shown in Fig. 1a. The elevation in the northern portion of the plain, near Nakhon Sawan, is approximately +25 m mean sea level (MSL) and is approximately +2 m MSL in the vicinity of Bangkok. The lower central part is characterized by a flat, broad, low lying, depositional surface, and is composed of three types of alluvial deposits: deltaic marine, flood plain, and alluvial fan. The major drainage system of the central plain is the Chao Phraya River and its tributaries. The Department of Mineral Resources has identified and named nine aquifers within the vicinity of Bangkok as shown in Table 1. Bedrock has been identified as deep as 1800 m in the few deep wells which were drilled in Bangkok (Achalahabhuti, 1974).

Table 1 Aquifers Identified by DMR to Depth of 550 m (Metcalf and Eddy Inc., 1977)

Aquifer	Depth (m)	Thickness (m)	Description
Upper Bangkok	20 to 30	1 to 30	Fine to coarse sand with gravel.
Lower Bangkok	30 to 50	1 to 50	Fine to coarse sand with gravel and clay layers.
Phra Pradaeng	60 to 100	1 to 70	Fine to coarse sand with gravel and clay layers.
Nakhon Luang	110 to160	5 to 70	Sand and gravel interbedded with clay.
Nonthaburi	180 to 200	5 to 60	Sand and gravel interbedded with clay and silt.
Sam Kok	240 to 250	10 to 55	Sand and gravel layers interbedded with clay.
Phya Thai	295 to 320	10 to 40	Sand and gravel layers interbedded with clay.
Thonburi	350 to 435	50 to 110	Sand and gravel layers interbedded with clay.
Paknam	530	30	Sand and gravel interbedded with clay.

Table 2 Summary of Physical Properties of Bangkok Clays (Oonchittikul, 1989)

Layer	w	w_L	I_p	e	γ_t (kN/m^3)	c_u (kPa)	ϕ
Weathered Clay	30-100	30-90	15-50	n.a.	15.2-18.6	20	n.a.
Soft Clay	40-110	40-120	20-85	1.3-3.8	14.2-17.2	5.9-26	n.a.
First Stiff Clay	15-40	25-90	10-50	0.4-1.2	17.7-21.1	29-260	n.a.
First Sand	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	30-40
Second Stiff Clay	15-35	30-70	15-45	0.8-1.3	17.7-22.1	59-210	n.a.
Second Sand	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	37-47
Third Stiff Clay	16-24	41-69	25-52	0.4-0.7	19.8-20.4	59-290	n.a.

Typical of these types of alluvial deposits, the soil underlying Bangkok generally consists of alternating layers of clay and sand. There is a surficial layer of soft to medium clay approximately 15 to 20 m thick that is commonly referred to as *soft Bangkok clay*. There is usually a desiccated crust approximately 2 m thick associated with this layer. The soft clay is underlain by a layer of stiff clay known as the *first stiff clay*. This layer is underlain sequentially by the *first sand layer*, the *second stiff clay*, and the *second sand layer*. A summary of the basic soil properties and shear strength parameters for the different layers is shown in Table 2 (Oonchittikul, 1989).

Though a considerable amount of general information regarding the various soil layers underlying Bangkok is available as seen from the data presented above, more detailed site specific data was needed to develop accurate estimates of the shear wave velocity profiles for the Bangkok metropolitan area. For this reason, detailed field and laboratory data was obtained from over 44 soil borings found in the literature (Amarasinge, 1993; Brand and Arbhabhirama, 1973; Kanjanakaroon, 1977; Tonyagate, 1978; Worayingyong, 1973), as well as from local consultants for nine sites around the Bangkok metropolitan area. A map showing the location of each of the sites is presented in Fig. 1b. Based on the general information reviewed and the site-specific data obtained, the generalized soil profile for Bangkok was developed as shown along the right margin of Fig. 2. For this profile, shear wave velocities were calculated from the specific data obtained from the nine sites and are presented in the following section. Based on these estimates, the generalized shear wave velocity profile for Bangkok was developed for use in this study.

ESTIMATION OF SHEAR WAVE VELOCITY

Researchers have been formulating various correlations between shear modulus or shear wave velocity for over thirty years. These range from correlations aimed at developing a fundamental understanding of soil behavior (e.g. Hardin and Drnevich, 1972b) to practical relationships aimed at estimating shear modulus with a minimum of information (e.g. Fumal, 1978) and include relationships based on field (e.g. Sykora and Stokoe, 1983) and laboratory data (e.g. Shibuya and Tanaka, 1996). The disturbance inherent in obtaining soil samples for subsequent laboratory testing makes it extremely difficult to measure values of low-strain shear modulus representative of the in situ conditions, particularly for cohesionless soils. Therefore, in situ soil testing, such as the Standard Penetration Test (SPT) and the Cone Penetration Test (CPT) have become the primary methods of estimating V_s of soil in situ, with the exception of direct measurement. Sykora (1987) and more recently Dickenson (1994) presented a thorough review of correlations.

For this project, it was our intent to utilize many of these existing correlations in order to develop an estimated shear wave velocity profile for Bangkok soils prior to conducting an in situ testing program. For each of the soil layers, three existing correlations were selected based on a variety of criteria, including the availability of data, appropriateness of the correlation for the subject soil, ease of use, and history of past use. Based on review of the estimated values, a best estimate V_s profile, as well as upper and lower bound profiles were developed. A description of the relationships used for each of the soil layers is presented below.

Estimation for Soft Bangkok Clay

The three relationships used for estimating shear wave velocity in soft Bangkok clay were those proposed by Hardin and Drnevich (1972b), Dickenson (1994), and Seed and Idriss (1970). Hardin and Drnevich (1972a) examined the effect of various parameters affecting the stress-strain relations in soils in the strain range

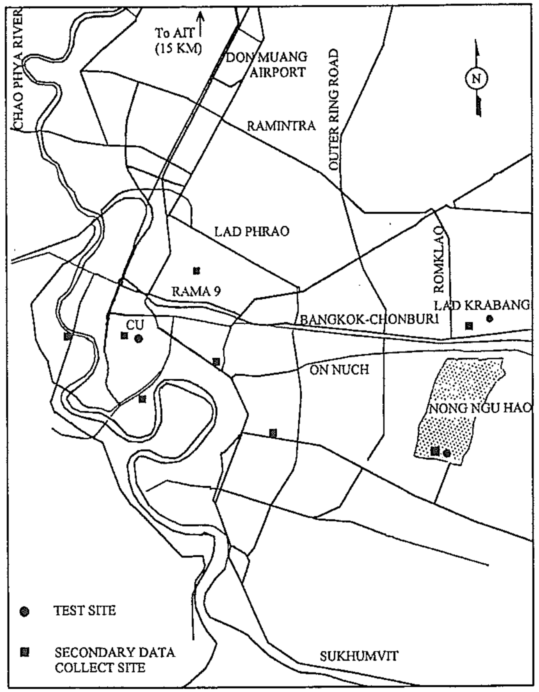

Fig. 1b Map Showing Thailand's Lower Central Plain (a), as well as the Location of Data Collection Sites and In Situ Testing Sites (a and b)

of 1% and less using results of the resonant column and cyclic simple shear testing. Hardin and Drnevich (1972a) concluded that strain amplitude, effective mean principal stress, and void ratios are very important factors, for both clean sands and clays.

Using the results of their earlier study, Hardin and Drnevich (1972b) subsequently developed a relationship for G_{max} as a function of void ratio, OCR, plasticity index, and mean effective stress. This classic relationship was used to estimate V_s for the soft Bangkok clay,

$$G_{max} = A \cdot \frac{(2.973-e)^2}{(1+e)} \cdot OCR^k \cdot \sigma_m^{0.5} \qquad (1)$$

where A is a constant equal to 3230 when σ_m, the mean effective stress, is in units of kPa, and k is a parameter based on the plasticity index of the soil. For soft Bangkok clay, k ranges between 0.18-0.48. The OCR used in this study is 1.2. An at-rest earth pressure coefficient of 0.61 was used in calculating σ_m. In this case, the G_{max} must be converted to V_s by utilizing the relationship between G_{max}, V_s, and γ_{soil}.

Dickenson (1994) presented the results of a study of the dynamic response of soft and deep cohesive soils during the 1989 Loma Prieta earthquake. He developed a non-linear relationship between shear wave velocity determined from field testing and undrained shear strength for four cohesive soil units in the San Francisco Bay area: San Francisco Bay Mud, Yerba Buena Mud, Alameda Formation (marine), and Alameda Formation (oxidized). The relationship includes both the soft S.F. Bay mud, as well as the deeper and stiffer old bay clays of the Alameda Formation. According to Jakrapiyanun *et al.* (1995) as shown in Table 3, the San Francisco Bay Mud on which Dickenson's (1994) formula is based and soft Bangkok clay are quite similar. For this reason, it was selected as one of the correlations used to estimate the V_s for the soft Bangkok clay. The relationship of Dickenson (1994) is:

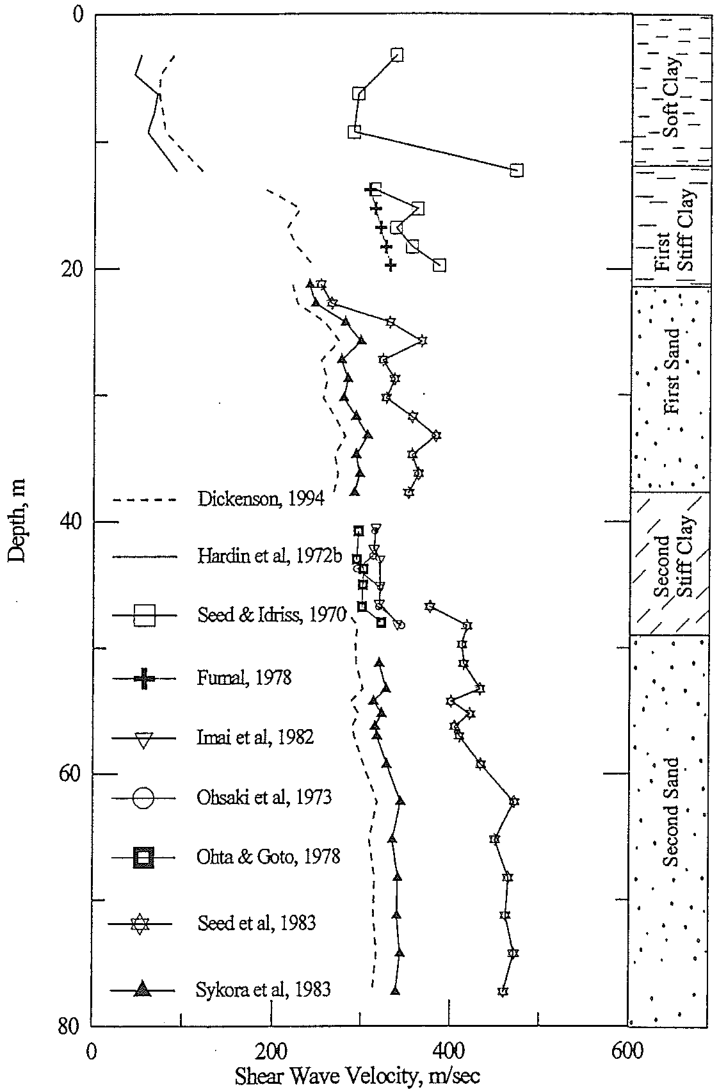

Fig. 2 Generalized Soil Profile for Bangkok and Estimated Shear Wave Velocities for Each Soil Layer Based on Selected Empirical Correlations

$$V_s = 68.7 \cdot c_u^{0.475} \quad \text{(m/s)} \tag{2}$$

where c_u has units of kPa. It should be noted that c_u determined from unconfined compression, unconsolidated undrained triaxial (TX), and consolidated undrained triaxial tests were used directly in the equation of Dickenson (1994). Field vane strengths were corrected using Bjerrum's plasticity-based correlation (Bjerrum, 1972), and the direct simple shear (DSS) strengths were modified using an assumed relationship of $(c_u)_{TX} \approx 1.35(c_u)_{DSS}$. The relationship showed good agreement with the data, but Dickenson suggested that all such relationships be verified for specific soils by field-testing.

Seed and Idriss (1970) developed one of the initial relationships relating small shear strain modulus to c_u based on an empirical study of 21 clays involving predominantly laboratory data. For comparison, the correlation between G_{max} and c_u proposed by Seed and Idriss (1970) was also used in this study. They proposed a linear relationship as follows:

$$G_{\max} = 2200 \cdot c_u \tag{3}$$

where the shear modulus and the undrained shear strength are in the same units. Though this relationship has been found to overestimate the G_{max}, and thus V_s, it was used for comparative purposes since it was used in earlier studies (e.g. Bergado *et al.*, 1986). However, subsequent researchers have shown that the ratio G_{max}/c_u, called normalized modulus, is not constant, but depends on c_u, *OCR*, I_p, and effective confining stress (e.g. Trudeau *et al.*, 1974; Koutsoftas and Fischer, 1980; and Egan and Ebeling, 1985). The results of these estimates based on the soil data obtained around Bangkok are presented in Fig. 2.

Estimation for the First Stiff Clay

Due to the lack of data concerning OCR, and the wide range of the OCR from the limited available data, the correlations used to estimate shear wave velocity for the first stiff clay differs from those used for soft Bangkok clay. Hardin and Drnevich's (1972b) correlation, which depends on OCR, could not be applied. However, the correlation based on undrained shear strength by Dickenson (1994) could still be used with the available data, as well as the correlation from Seed and Idriss (1970) for comparison.

In addition, continuing our comparison to the San Francisco Bay area, a relationship proposed by Fumal (1978) based only on depth for soil in the San Francisco was used. Fumal (1978) collected and analyzed downhole seismic data from 59 sites throughout the San Francisco Bay region and determined a correlation for the variation of V_s with depth:

$$V_s = 182.068 \cdot z^{0.20} \quad \text{(m/s)} \tag{4}$$

where z is in meters. Fumal's relationship applied not only to S.F. Bay Mud, but to sand, stiff clay, and gravely soil as well. The results for the first stiff clay layer based on these three relationships using the data from the various Bangkok sites are also presented in Fig. 2.

Estimation for the First and Second Sand Layer

Due to the lack of data for the first and second sand layers, the correlations used to estimate V_s were based solely on N-value obtained from the Standard Penetration Test (SPT). The first sand layer for Bangkok occurs at a depth of 20 to 30 meters; for the sake of simplicity, an intermediate depth of 25 meters was assumed for the upper surface of the first sand layer and that the thickness was 25 meters. For the estimation of V_s for the first sand layer, it was assumed that the efficiency of all SPT N-value data are standard (N_{60}) are equal to 60%, and all tests were conducted in general accordance with ASTM D1586-84 (ASTM, 1989).

Table 3 Comparison of soft Bangkok clay to San Francisco Bay Mud

Soil	Thickness (m)	γ_t (kN/m^3)	w_L	I_p	w	c_u/σ_n	*OCR*
Bangkok Clay	15-20	14.2-17.2	40-120	20-85	27-78	0.27-0.35	1.1-1.3
S.F. Bay Mud	17-18	14.2-17.8	42-119	23-62	35-120	0.24-0.40	1.0-1.5

Three different correlations were used. The first was proposed by Dickenson (1994), who formulated the relationship for sand in the San Francisco Bay area, and where the only parameter in the formula is N:

$$V_s = 88.392 \cdot (N+1)^{0.3} \quad \text{(m/s)} \tag{5}$$

Seed, Idriss, and Arango (1983) suggested using the following equation for sand and silty sand to assess shear wave velocity also based solely on N:

$$V_s = 56.388 \cdot N^{0.5} \quad \text{(m/s)} \tag{6}$$

Sykora and Stokoe (1983) published correlations between the shear wave velocity and N for cohesionless soils. This third relationship, used in the estimation of V_s for the first sand layer, is:

$$V_s = 100.584 \cdot N^{0.29} \quad \text{(m/s)} \tag{7}$$

The results of the estimation are shown in Fig. 2 for the data from the study sites. It should be noted that the SPT is often performed in Thailand using a "donut" type drive weight with an efficiency of about 45% (Seed *et al.*, 1985). This decreased efficiency would increase the N-values by about 30%, but would have increased the results V_s values by less than 5%, and thus would have had little effect on the outcome of this study.

Estimation the Second Stiff Clay

For the estimation of the shear wave velocity for the second stiff clay layer, three relationships developed for any soil type based solely on uncorrected N were used. The first was proposed Imai and Tonouchi (1982), who synthesized data from 400 sites throughout Japan, 1654 sets of data in all, and developed the following relationship:

$$V_s = 96.926 \cdot N^{0.314} \quad \text{(m/s)} \tag{8}$$

The second is based on 200 sets of V_s data (Ohsaki and Iwasaki, 1973), collected by predominantly the downhole method, throughout Japan. They developed correlations between shear modulus and uncorrected N, geologic age, and soil type. Ohsaki and Iwasaki (1973) then presented the following equation for all soil types, assuming a constant unit weight of 17.66 kN/m^3, they presented the following relationship between V_s and uncorrected N:

$$V_s = 81.686 \cdot N^{0.39} \quad \text{(m/s)} \tag{9}$$

Ohta and Goto (1978) developed the last. Ohta and Goto (1978) accumulated and analyzed almost 300 sets data from soils in Japan. The data analysis was carefully thought out regarding shear wave velocity, geologic age, depth, N, and soil type. They developed 15 empirical formulae the most general of which is shown below, which involves only N:

$$V_s = 85.344 \cdot N^{0.341} \quad \text{(m/s)} \tag{10}$$

The results of the estimation using the 3 equations for the data from the Bangkok study sites are presented in Fig. 2.

Figure 3 presents our best estimate, upper bound, and lower bound V_s profiles for the generalized Bangkok soil profile. These best estimate and upper and lower bounds were selected based on review of the range of results using the various correlations and on engineering judgment.

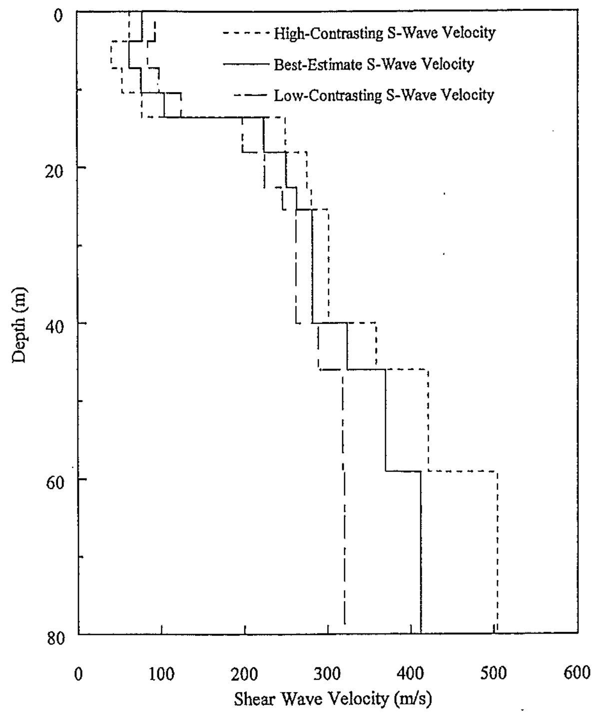

Fig. 3 Best Estimate V_s Profile Based on Field and Laboratory Data Correlations

MEASUREMENT OF SHEAR WAVE VELOCITY

Though much effort was put forth in this research program using empirical relationships to estimate the shear wave velocity profile for Bangkok, when possible, it is desirable to confirm such estimates with actual in situ measurements. With this purpose, the in situ shear wave velocity profile was measured at four locations around Bangkok using the downhole method: Asian Institute of Technology (AIT), Chulalongkorn University (CU), Lad Krabang (LK), and Nong Ngu Hao (NNH). The locations of these sites are shown in Fig. 1. These four sites were selected to cover a range of in situ conditions, as well as for convenience. All of the sites, except CU, had existing cased boreholes that could be used for downhole V_s testing. The AIT site is located on the north edge of the greater Bangkok metropolitan area, where the soft Bangkok clay tends to be older. Both LK and NNH are based on the eastern portion of Bangkok, where much development is ongoing, and where the soft Bangkok clay is somewhat younger. NNH is also the site for the New Bangkok International Airport, and has been the subject of much previous geotechnical study. CU, where the only new borehole was required, is located at the heart of Bangkok, where a limited amount of fill has been in place for many years. These are believed to be the first such measurements obtained for the soil underlying Bangkok, including for the soft Bangkok clay.

In all, 5 boreholes were tested. To make efficient use of available funds, four of the five were previously existing cased boreholes. At AIT, an abandoned water well of 200mm diameter steel casing was tested to a depth of 61 meters. In addition, a 75mm diameter PVC casing was tested to 8m depth at the edge of a 4-m high-reinforced earth wall. At LK, a 150mm PVC water monitoring well was tested to a depth of 14m. Two sets of tests were conducted on right angles to test for anisotropy at the Nong Ngu Hao site, where a 70-mm slope inclinometer casing was used to a depth of 13m. The final site tested was at Chulalongkorn University, at the heart of Bangkok. A new borehole with 70mm PVC casing was tested to a depth of 30m.

Method

A shear wave velocity profile was developed at each site using the downhole method in order to provide a quantitative measure of the shear modulus variation as a result of the stratigraphic variability and depth. In the downhole method, the travel time of the signal is measured between the source at the ground surface and a receiver in the borehole. The source was a 6.4-kg hammer striking a horizontal blow to the steel endplate of a 2-meter long, 150mm by 150mm teak plank. The plank had metal cleats that assisted in transferring the load to the ground surface, and in addition, the plank was held in place by the front wheels of a truck resting on its top. The hammer blow generated a horizontally polarized shear wave that traveled through the soil.

The downhole receivers for the shear wave impulse were a pair of horizontal geophones inside the tool casing. All of the boreholes were cased; two with inclinometer casing. For these boreholes, the geophones were kept in line with the source by using a rod to guide the tool along the grooves of the inclinometer casing. Having the geophone always in line with the plank optimized the shear wave signal, thus leading to excellent quality data. In another attempt to optimize the quality of the data, generally each end of the plank was struck for each test depth. This resulted in signals of opposite polarity, which were used to check for anomalies in the data and to confirm the velocity at each depth. The geophone housing was held in place at each test depth with a motorized arm. Signals were recorded on an EG&G Geometrics 24-channel digital seismograph.

Results and Discussion

The interpreted V_s profile based on the travel time plots are presented in Fig. 4, along with the previously estimated range of V_s based on the field and lab correlations.

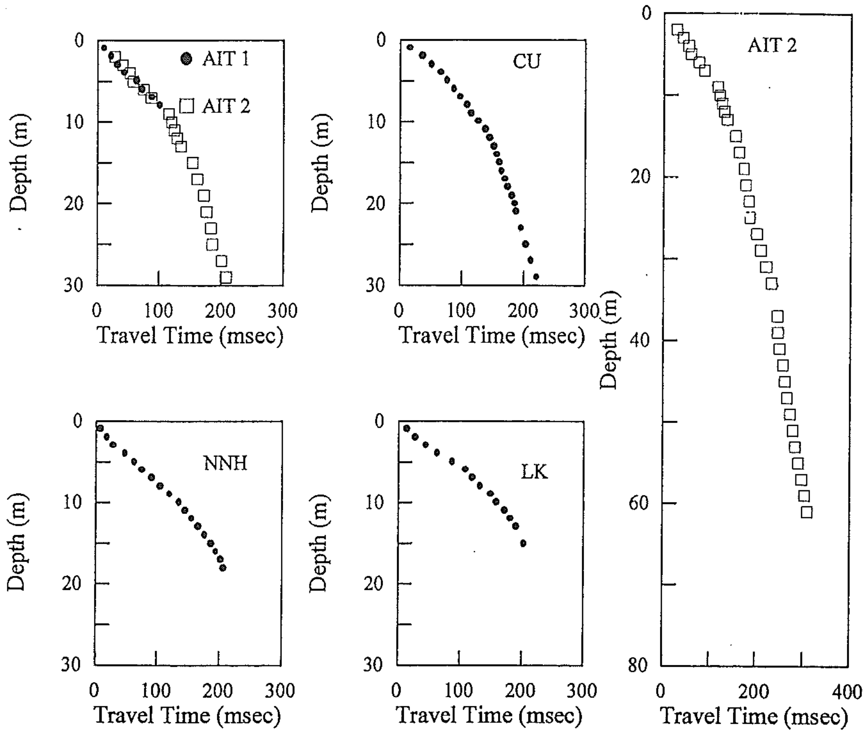

Fig. 4 Travel Time Plots for Each Test Site

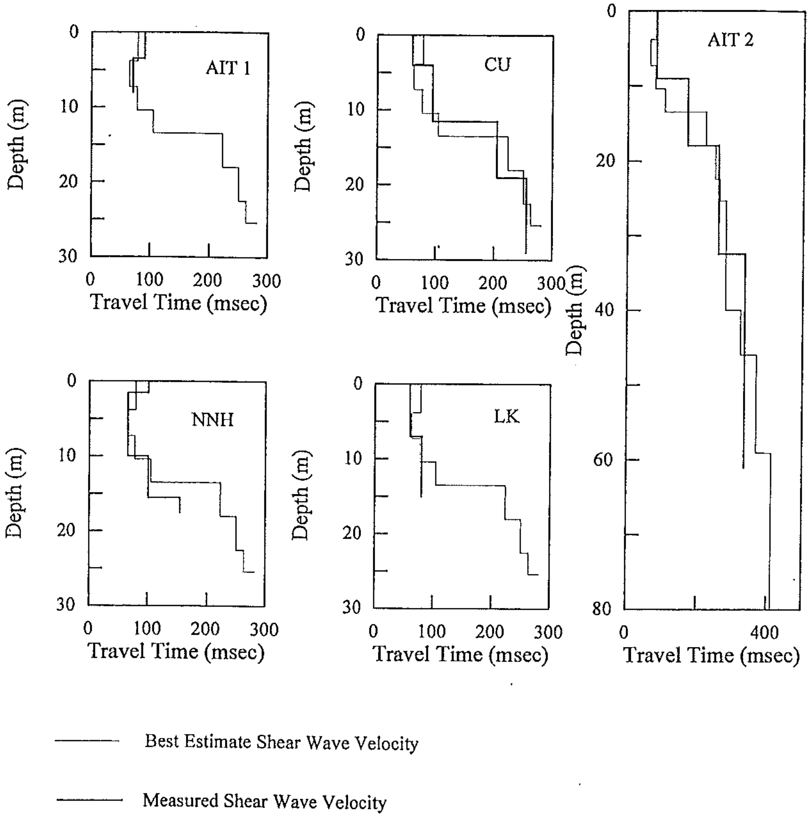

Fig. 5 Comparison of Estimated and Measured V_s Profiles for Each Test Site

In general, the results show extremely low values of shear wave velocity in the soft Bangkok clay. Reviewing the data at all four sites, V_s does not exceed 100 m/s for the soft Bangkok clay for the entire depth of 9 to 15 meters, and is as low as 60 m/s to 80 m/s at all sites. In addition, very little difference, if any, is observed between the surficial crust or man-made fill and the underlying soft clay. This would indicate the fill is in a loose or poorly compacted state. It can be seen from the V_s profiles at AIT, CU, and NNH that the values increase considerably in the first stiff clay layer, ranging from 155 to 205 m/s. The underlying first sand layer has a V_s of approximately 260 m/s as shown from the profiles at CU and AIT. In addition, the AIT profile shows that both the second sand and stiff clay layers have V_s on the order of 335 m/s. Regarding anisotropy in the soft Bangkok clay, essentially identical results were obtained for both the N-S and E-W directions, indicating no significant anisotropy.

The measured shear wave velocities are compared in Fig. 5 to our best estimate shear wave velocity profile for the generalized Bangkok soil profile. The comparison shows good agreement for all layers, including the soft Bangkok clay. This indicates that the empirical correlations used in estimating the V_s profiles were reasonable and appropriate. The extremely low values of V_s in the soft clay are quite unusual and the best estimate profile is compared in Fig. 6 to noted soft clays from around the world. The values for soft Bangkok clay are, in fact, lower than the values for San Francisco or Tokyo, and actually approach values obtained for Mexico City clay (which can have V_s as low as 40 m/s), which contributed to so much destruction in the 1985 Mexico City earthquake (Seed *et al.*, 1987).

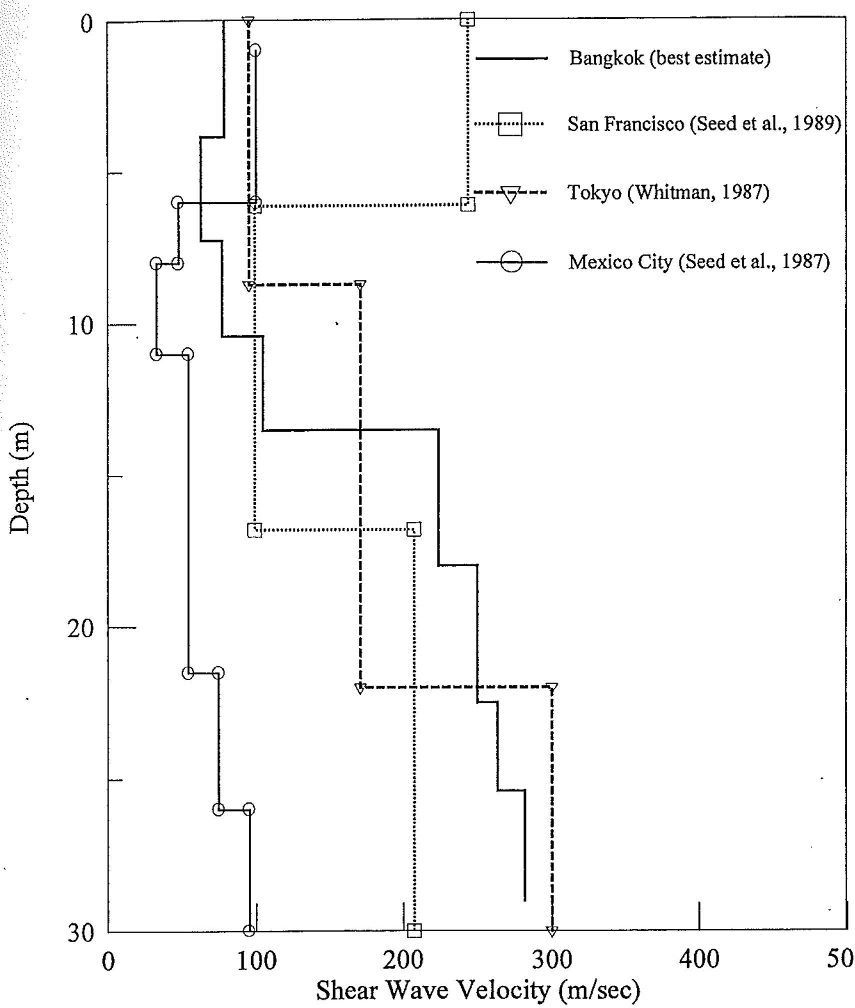

Fig. 6 Comparison of V_s of Soft Bangkok Clay to Other Clays Around the World

In Fig. 7, the measured shear wave velocities are compared to estimated values from an earlier study (Bergado *et al.*, 1986) based on the empirical correlations proposed by Seed and Idriss (1970) as discussed earlier. It can be seen that the Seed and Idriss (1970) relationships overestimate the V_s in all layers, and for the soft Bangkok clay, the values are overestimated by a factor of 2 to 3. These differences are pointed out because earlier seismic site response studies (e.g. Bergado *et al.*, 1986; Lukkunaprasit, 1989) were based on V_s estimates based on Seed and Idriss (1970). The results of seismic site response analyses based on the estimated values of V_s obtained in this study will be significantly different than the results of earlier studies. The differences will likely be reflected in greater amplification and peak spectral response at longer periods due to the slower V_s. In addition, the specific impedance ratio between the soft Bangkok clay and the underlying first stiff clay layer is in excess of 2, and will also contribute significantly to amplification of earthquake ground motions.

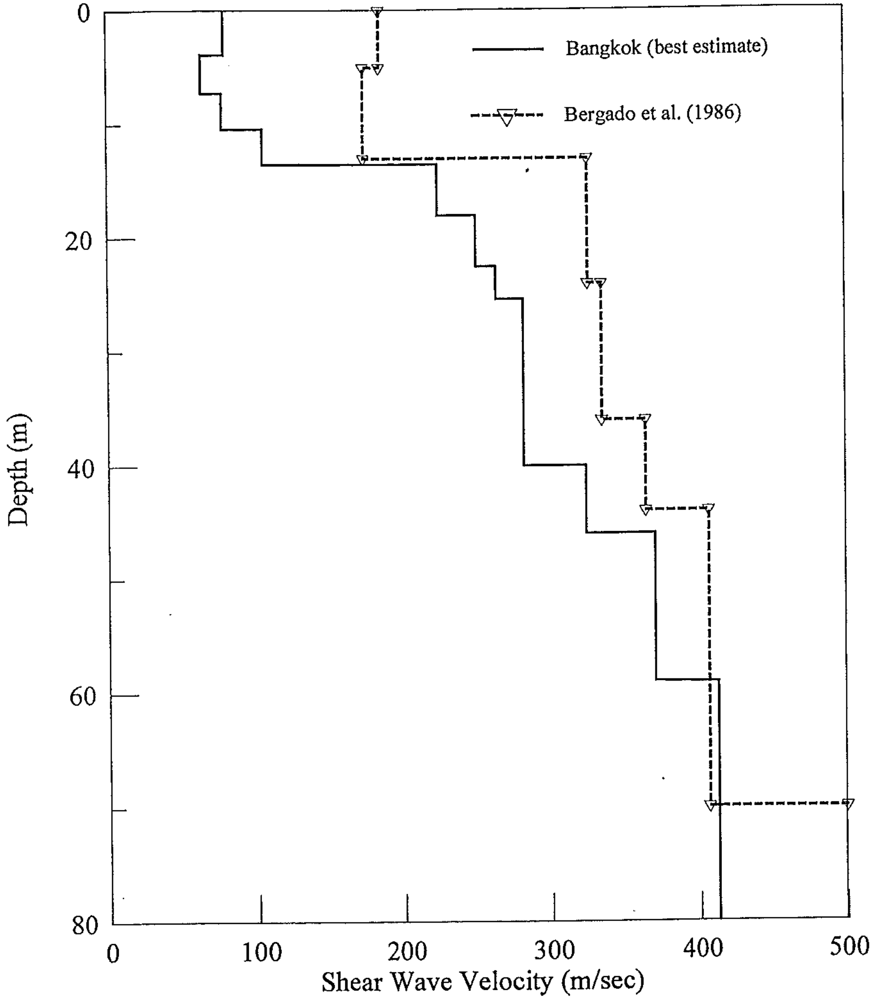

Fig. 7 Comparison of Estimated V_s Profile for Bangkok to Previous Study

CONCLUSIONS

1. Good agreement was found between the estimated and measured shear wave velocity profiles, particularly for the soft Bangkok clay when using the correlations developed for San Francisco Bay Mud.

2. The shear wave velocity for soft Bangkok clay is extremely low (between 60 and 100 m/s). This is in general lower than that of San Francisco Bay Mud and comparable to Mexico City clay.

3. The extremely low shear modulus of the soft Bangkok clay and high specific impedance ratio between it and the underlying soil layer are ideal conditions for soil amplification of earthquake ground motions, particularly low amplitude motions from distance earthquakes, and justify renewed efforts at quantifying the seismic risk facing the greater Bangkok metropolitan area.

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