Bulletin of Earthquake Engineering (2020) 18:1139–1159
https://doi.org/10.1007/s10518-019-00767-1

ORIGINAL RESEARCH

Correlations between Vs and SPT-N by different borehole measurement methods: effect on seismic site classification

Chih-Chieh Lu[1] · **Jin-Hung Hwang**[2]

Received: 21 May 2019 / Accepted: 29 November 2019 / Published online: 5 December 2019
© Springer Nature B.V. 2019

Abstract

The average shear wave velocity of the top 30 m of the subsurface profile (Vs30) is a critical parameter to characterize the seismic site class. Since Vs30 is a quantitative index and measurable by geophysical techniques, the use of Vs30 becomes popular and is widely used in practice. However, the Vs30 of a site may vary due to the different Vs measurement methods used. This could result in a different seismic site class and design force. To quantify the effect of measurement methods on Vs and seismic site classification. This study collected high quality geotechnical investigation reports with standard penetration test (SPT) N-values, and shear wave velocities measured by suspension logging, SCPT, down-hole test and cross-hole logging. The correlations between Vs and SPT-N by different methods were then built and compared. The results show that Vs by suspension logging is relatively high in comparison with those by SCPT and cross-hole logging. The effect on the site classification resulting from the different Vs measurement methods is then demonstrated with several examples.

Keywords Shear wave velocity · Measurement methods · Vs-N correlations · Site classification

1 Introduction

In modern seismic design codes, the elastic response spectrum of earthquake ground motion is commonly adopted to determine the seismic design forces of buildings and other structures. However, the shapes of earthquake response spectrum are significantly influenced by site geology and local soil conditions. Thus, the pioneer work of Seed et al. (1976) proposed the first site-dependent spectra for earthquake resistant design. In their

---

✉ Chih-Chieh Lu
chchlu@ncree.narl.org.tw

Jin-Hung Hwang
hwangjin@cc.ncu.edu.tw

[1] National Center for Research on Earthquake Engineering, No. 200, Sec. 3, Xinhai Rd., Taipei 10668, Taiwan, ROC

[2] Department of Civil Engineering, National Central University, No. 300, Jhongda Rd., Zhongli District, Taoyuan 32001, Taiwan, ROC

Table 1 Summary of the site categories by Vs30

BSSC (2003)		MOI (2011)		Description
Vs30 (m/s)	Site class	Vs30 (m/s)	Site class	
> 1500	A	> 270	I	Hard rock
760–1500	B			Rock
360–760	C			Very dense soil/soft rock
180–360	D	180–270	II	Stiff soil
< 180	E	< 180	III	Soft soil
–	F	–	–	Special soils requiring site-specific evaluation

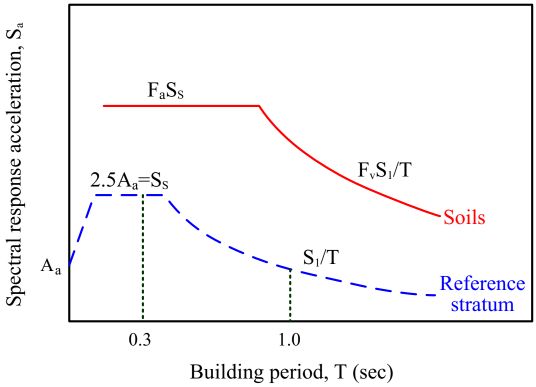


Fig. 1 Illustration of spectral response acceleration subject to reference stratum and soils (modified from Dobry et al. 2000)

work, the seismic sites were classified into four kinds from rock, deep stiff soil to soft soil using qualitative descriptions. In the 1991 version of the National Earthquake Hazards Reduction Program (NEHRP) Provisions, the site classification was basically based on a semi-quantitative description similar to that of Seed et al. (1976). Thus, some engineering judgments are required for site classification (BSSC 1985, 1988, 1991). However, based on the research results of Dobry et al. (2000), the recent seismic design code of the FEMA (e.g., the 2015 version of the NEHRP Provisions) used a representative average shear wave velocity of the top 30 m of the subsurface profile (Vs30) to quantitatively consider the effect of local soil conditions on ground motion. According to the site's velocity profile, the site can be classified into its own site class uniquely with its Vs30. Table 1 shows current site classification criteria with respect to Vs30 by BSSC (2003) and MOI (2011). Since Vs30 can provide unambiguous site classification and is also measurable by geophysical methods, thus the Vs30 approach becomes popular and is widely used in practice. In this approach, the site classification is determined first by its Vs30. Then, the site coefficients (F_a and F_v) are obtained according to its class. The design response spectrum is then derived by multiplying the reference spectrum with F_a and F_v at its short and long period parts as shown in Fig. 1. By this way, the effect of local soil conditions on the design seismic force of a structure is taken into account.

Even though the definition of Vs30 is clear, there is still doubt whether different seismic methods yield the same results since the new site classification was introduced in 1994.

Furthermore, whether the Vs30 value of a site may vary much due to the different Vs measurement methods, which could result in a different site class and design seismic force. It is the issue that this study wants to address.

Regarding the researches on the shear wave velocity of alluvial soils, the key influencing parameters such as geological age, void ratio, plasticity index, soil type, effective stress state, over-consolidation ratio, etc. have been studied and clarified by several early studies, and Sykora (1987) provided a comprehensive summary. Anbazhagan et al. (2016) studied the correlation of densities with Vs and SPT-N. Garofalo et al. (2016) reported the execution of the InterPACIFIC project and assessed the results of several Vs measurements at three different subsoil conditions. L'Heureux and Long (2017) used the data measured by several geophysical seismic methods and SCPT-u to compare the Vs differences due to measurement method and establish the Vs-q_c correlation of Norwegian clays. Due to the demand of practical use, numerous correlation studies have been conducted to directly examine a relationship between Vs and SPT-N (Imai and Yoshimura 1975; Sykora and Stokoe 1983; Sykora and Koester 1988; Jafari et al. 2002; Anbazhagan and Sitharam 2006; Hasancebi and Ulusay 2007; Hanumantharao and Ramana 2008; Ulugergerli and Uyanık 2007; Unal 2009; Maheswari et al. 2010; Kumar et al. 2010; Akin et al. 2011; Tsiambaos and Sabatakakis 2011; Chaterjee and Chaudhury 2013; Marto et al. 2013, Jhinkwan and Jain 2016; Kirar et al. 2016). Wair et al. (2012) provided a summary of the above researches on the Vs estimation based on SPT data and gave the recommendation in estimating the Vs of the top 30 m of the soil profile (Vs30). Of course, it is better to conduct the in situ Vs measurement directly for each project, and evaluate the site classification according to the results of Vs measurement. However, in most of practical cases, only SPT borehole would be conducted and the Vs measurement is always ignored due to the limit of budget. Thus the use of some empirical Vs-N relationships for the evaluation of Vs becomes very popular in engineering practices. However, it should be noticed that the databases for the Vs-N regression analysis are generally collected from different Vs measurement methods. Although it is well known and proved by several studies that cross-hole testing is the most reliable Vs acquisition method. However, few researches used the databases based on cross-hole testing while conducting the Vs-N regression analysis. This is because cross-hole testing needs to bore two holes and the cost is expensive. Thus its data base is relatively insufficient.

There are two purposes in this study. The first one is to clarify the difference of the measured Vs due to the different geophysical seismic methods in Holocene alluviums, and provides some comments on the discrepancy accordingly. The other one is to suggest a set of Vs-N regression curves based on the reliable databases collected from the several Vs measurement methods including the cross-hole seismic testing, SCPT, and suspension logging for practical use. The suggestion of Vs-N regression curve based on the cross-hole seismic method is believed to be useful and important for practical engineering use. This study first collected many high quality site investigation reports of important projects in Taiwan, and established a database including information on the soil types, the SPT-N-values, and the measured shear wave velocities (Vs) by different seismic measurement methods, such as suspension logging, SCPT, and cross-hole logging. The correlations between Vs and SPT-N were then built for different soil types and compared with each other. Based on the results, the measured Vs from suspension logging yielded significantly high shear wave velocity in comparison with the ones from SCPT and cross-hole logging. The reasons were discussed in the aspects of borehole treatment. Finally, the effect of the different Vs measurement methods on the site classification was then demonstrated with several examples.

2 The seismic design code for building structures in Taiwan

The seismic design code for buildings and other structures in Taiwan essentially follows the recent FEMA system (Construction and Planning Agency, MOI 2011), with some modifications according to the local conditions in Taiwan. For all surface structures, sites are classified as shown in Table 1. Note that the reference strata are different between the systems of FEMA and MOI. The reference strata defined by FEMA is the one with Vs30 > 760 m/s; however, the reference strata defined by MOI only has the Vs30 > 270 m/s. The site classification system of Taiwan originally followed the FEMA system. However, in Taiwan, the free-field seismic stations with Vs30 > 760 m/s is rare. Therefore, while conducting the probabilistic seismic hazard analysis to determine the seismic spectrum of reference stratum in a return period of 475 years, the seismic stations at the sites with Vs30 ranging from 270 to 760 m/s have to be included due to insufficient seismic records. This makes the site classification system of Taiwan has only 3 classes. The stratum with Vs30 > 270 m/s belongs to Site Class I; the one with Vs30 ranging from 180 to 270 m/s is Site Class II, and the one with Vs30 < 180 m/s belongs to Site Class III.

For site classification, Vs30 should be calculated as 30 m divided by the sum of the travel times for shear waves to travel through each layer. As shown in Eq. (1), the travel time for each layer is calculated as the layer thickness (d) divided by its Vs. For cases where measured Vs data is not available, the empirical relationship between SPT-N and Vs in sandy or fine-grained soils suggested by JRA (2002) would be commonly used to estimate Vs in terms of the SPT resistance.

$$\mathrm{Vs30} = 30/\Sigma(\mathrm{d/Vs}) \tag{1}$$

After that, the design spectral response acceleration parameters at the periods of 0.3 s (S_{DS}) and 1 s (S_{D1}) with adjustments for site effects can be calculated as follows:

$$S_{DS} = F_a S_s \tag{2}$$

$$S_{D1} = F_v S_1 \tag{3}$$

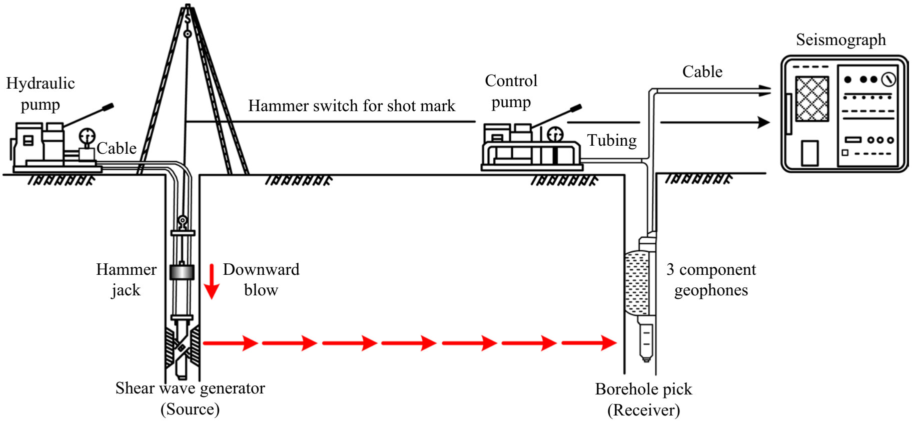
where S_s is the referenced stratum (Site Class I) spectral response acceleration at a short period, S_1 is the referenced stratum (Site Class I) spectral response acceleration at a period of 1 s, and F_a and F_v are the site coefficients to consider site effect. A designer should refer to MOI (2011) for the S_s and S_1 of each administrative division in Taiwan.

The framework of developing a local site spectrum is summarized in Fig. 1. In the figure, S_s, S_1, F_a, and F_v can be derived from the MOI (2011), and A_a is the effective peak ground acceleration which is about $S_s/2.5$.

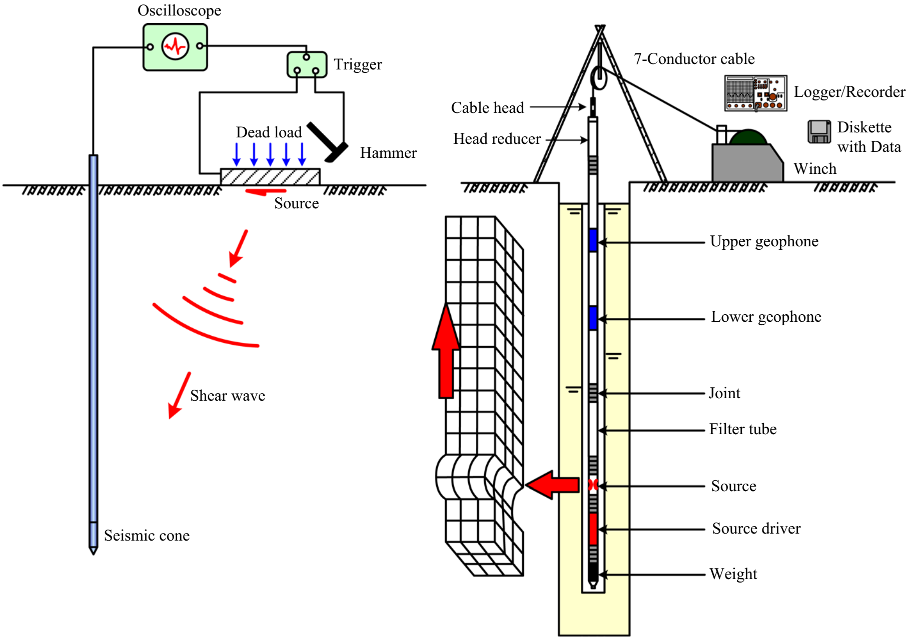
3 The database based on different Vs measurement methods

In practice, it is very common to adopt in situ geophysical seismic methods for estimating the shear wave velocities of geo-materials under a small strain level, and this has been incorporated into the site classification systems. In general, the geophysical methods can be divided into two categories: invasive and non-invasive. The main difference between them is the requirement of a drilling hole. Common invasive methods include downhole

(DH) and cross-hole (CH) loggings, suspension logging (PS), and the seismic cone penetration test (SCPT). Non-invasive geophysical methods include spectral analysis of surface waves (SASW), seismic refraction, and seismic reflection. In this paper, only the cross-hole logging, suspension logging, and seismic cone penetration test (SCPT) Vs measurement methods are discussed, and the corresponding field measured results were collected from



(a) Cross-hole testing (modified from Ishihara, 1996)



(b) Seismic cone penetrometer (modified from Ishihara, 1996)

(c) Suspension logging (modified from Nigbor and Imai, 1994)

Fig. 2 Field arrangements used to perform intrusive seismic tests some important engineering projects in Taiwan; Fig. 2 shows schematic diagrams of these methods. Table 2 is a modification of that from Andrus et al. (2004) to compare and summarize the features of these methods.

3.1 Sources used for the database

The database used in this study consists of field measured results based on the above Vs measurement methods collected from several important engineering projects located in the alluvium of western Taiwan over recent decades. The locations of these engineering sites are shown in Fig. 3. The basic information of the sites, as well as the references, is tabulated in Table 3. The information for each dataset consists of the depth, soil classification of the unified soil classification system (USCS), SPT-N value and the type of hammers, the measured shear wave velocity and the corresponding Vs measurement method, and the references. Note that while conducting SCPT sounding, because the SPT with the accompanying sampling process by split tube sampler was not used, neither the SPT-N nor the soil classification of the USCS (due to the lack of a soil sample for laboratory testing) were available. This required information is assumed to be the same as measurements from neighboring boreholes at the same depth for further regression work. In this study, the distance between the SCPT sounding and the reference SPT borehole were within about 20 m, and most of them are less than 10 m. In addition, the operation of the cross-hole seismic testing requires two boreholes, as shown in Fig. 2. In the collected cross-hole seismic testing cases, the standard penetration tests were carried out in all Vs-measuring boreholes, which means that a specific depth would have the results of one Vs measurement and two SPT-N values. Since each measured Vs at a specific depth would correspond to two SPT-N values from the two testing boreholes, in order to keep the origin of the raw data, the Vs measured by cross-hole seismic testing would be recorded in two datasets. Based on the above approach, the total number of documented datasets is 1189 (shown in Fig. 4). Among them, 317 datasets are from the recorded data using cross-hole seismic testing, 587 datasets are from the recorded data using SCPT, and the remaining 285 datasets are from the recorded data using the suspension logging testing. These datasets were screened based on selected criteria, and this is explained in the following section. The categorized datasets would then be used for the following regression work.

3.2 Data processing

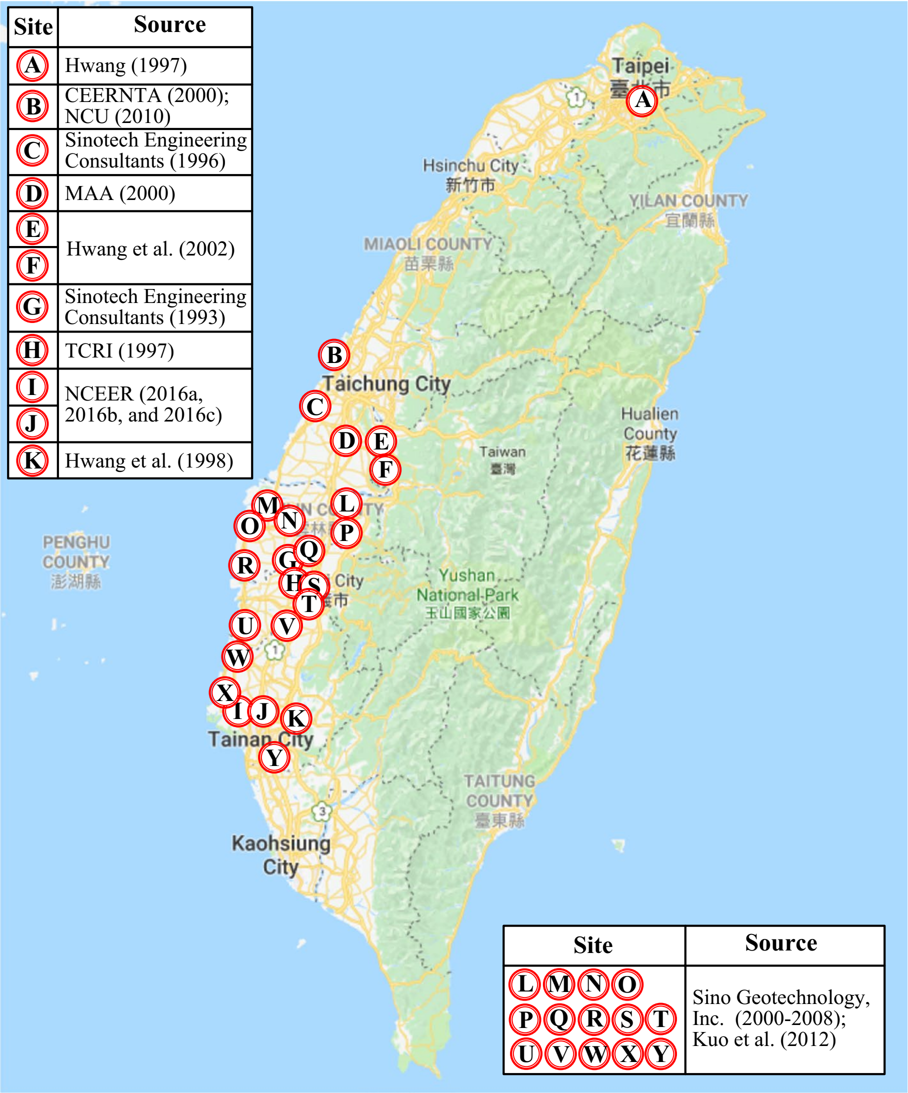
It is recognized that geologic considerations can aid in the estimation of Vs. The datasets shown in Fig. 4 were first divided by soil classification based on the USCS. In this study, the geologic units were divided into two groups, sandy soil and fine-grained soil. Note that the N_{60}-values of the datasets included in the sandy soil group were then screened out if the N_{60}-values were larger than 50. For the fine-grained soil group, the N_{60}-values of the datasets were screened out if the N_{60}-values were larger than 25. The consideration of this screening criterion is because the mechanical behaviors of "the sandy soils" with $N_{60} > 50$ and "the fine-grained soils" with $N_{60} > 25$ are similar to soft rock instead of soil based on the local experiences of Taiwan and Japan. Since the study focused on the N_{60}-Vs regressions of the alluvium soils, the datasets with N_{60} higher than the above threshold values are therefore deleted. The ones with SC, SM, SP, or SW of the USCS belong to the sandy soil group. In the sandy soil group, most of the soils do not have plasticity index (PI) except clayey sand (SC). The N_{60} of the soils

Table 2 Comparison of the concerned in situ Vs measurement methods (modified from Andrus et al. 2004)

Feature	Measurement method		
	CH	SCPT	PS
No. of holes required	2 or more	1	1
Quality control and repeatability	Good	Good	Good
Resolution of variability in stiffness of soil deposits	Good; constant with depth	Good to fair; decreases with depth	Good at depth; poor very close (3–6 m) to the ground surface
Limitations	Possible refraction problems; senses stiffer material at test depth; most expensive test method	Possible refraction problems with shallow layers; wave travel path increase with depth	Fluid-filled hole required; may not work well near the surface in cased holes and soft soils
Other	Highly reliable test; measurements at each depth independent of other depths; well suited for tomographic imaging; independent checking of saturation with compression waves is possible	Penetration data also obtained from seismic cone; detailed layered profile with cone	Well suited for deep borehole testing; method assumes shear waves travel in undisturbed soil.
PVC casing[a]	Yes	No	Yes[b]
Grouting[a]	Yes	No	Yes[b]

[a] Information added by the authors

[b] In Taiwanese engineering practice, the installation of PVC casing and grouting are usually adopted



Site	Source
A	Hwang (1997)
B	CEERNTA (2000); NCU (2010)
C	Sinotech Engineering Consultants (1996)
D	MAA (2000)
E	Hwang et al. (2002)
F	
G	Sinotech Engineering Consultants (1993)
H	TCRI (1997)
I	NCEER (2016a, 2016b, and 2016c)
J	
K	Hwang et al. (1998)

Site	Source
L M N O P Q R S T U V W X Y	Sino Geotechnology, Inc. (2000-2008); Kuo et al. (2012)

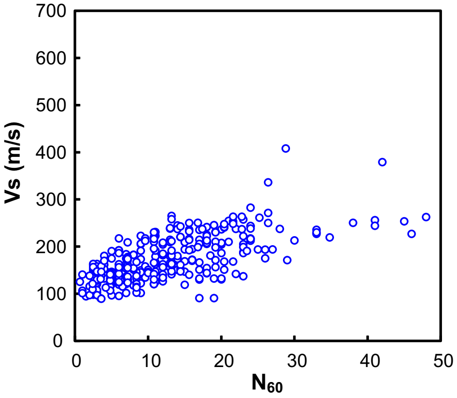
Fig. 3 The locations of the engineering sites

ranges from 1 to 49 and the average value is about 18. According to Terzaghi and Peck (1967), the relative density of the soils ranges from about 5 ~ 85% and the degree of compactness is from very loose to dense. The other ones with CL, CH, ML, or CL-ML of the USCS belong to the fine-grained soil group. In the fine-grained soil group, the plasticity index (PI) ranges from 0 to about 47. The N_{60} of the soils ranges from 1 to 25 and the average value is about 10. According to Terzaghi and Peck (1967), the consistency of the soils ranges from very soft to very stiff. The N_{60}-value represents the blow count number during performing standard penetration test. The subscript of N_{60} denotes the amount of energy transmitted to the sampler divided by the theoretical maximum

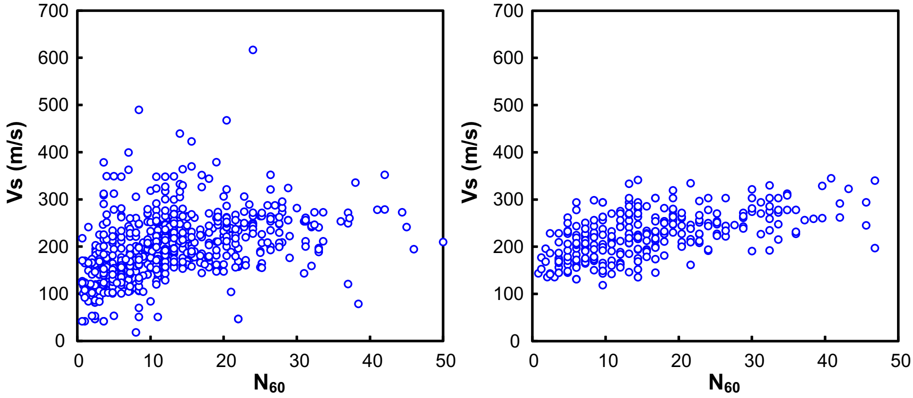
Table 3 Basic information for the sites

Site	Vs measurement method			Source
	Cross-hole logging	SCPT	Suspension logging	
A	V	V	–	Hwang (1997)
B	V	V	–	CEERNTA (2000) and NCU (2010)
C	V	–	–	Sinotech Engineering Consultants (1996)
D	V	V	–	MAA (2000)
E	V	V	–	Hwang et al. (2002)
F	–	V	–	Hwang et al. (2002)
G	V	V	–	Sinotech Engineering Consultants (1993)
H	V	V	–	TCRI (1997)
I	V	V	–	NCREE (2016a, b, c)
J	V	V	–	NCREE (2016a, b, c)
K	V	V	–	Hwang et al. (1998)
L-Y	–	–	V	Sino Geotechnology, Inc. (2000–2008) and Kuo et al. (2012)

SPT energy (64.5 kg dropped from a height of 76 cm) in percentage. In an attempt to minimize variability, the N-values were converted to a uniform reference energy ratio of 60% of the theoretical SPT energy (N_{60}). Due to the lack of energy measurement data for the different types of SPT hammers in the collected database, this study assumed a hammer energy ratio of 60% for rope-cathead hammer system, which is the most common type in Taiwan, and 72% for an automatic hammer system based on Japanese engineering practice. In order to facilitate the following correlations and comparisons, all SPT-N values were converted to the basis of energy ratio of 60%. The SPT-N value with the energy ratio other than 60% should be adjusted. For example, the SPT-N value done by automatic hammer system with the energy ratio of 72% should be multiplied by 1.2(72/60). After the data processing based on the above criteria, there were 6 categories (listed in Table 4). Note that some data were screened out, and the total number of datasets in the table is not the same as the original database. Data points of Vs versus N_{60} with respect to the different Vs measurement methods for the sandy soil and fine-grained soil groups (the 6 categorized datasets) as well as regression curves are shown in Figs. 5 and 6, respectively. According to the visual inspection on the figures, it can be seen that the cross-hole seismic testing datasets have a relatively small variation at any specific N-value when compared with the other two Vs measurement methods. The SCPT datasets typically had a significant amount of scatter in the measurements (as evident in Figs. 5b and 6b), which may result from the locations of the measured Vs differing from the locations of the SPT. In Figs. 5c and 6c, the Vs measured by suspension logging testing also has a small amount of scatter, and the measured Vs is similar to the results from cross-hole seismic testing when the N_{60}-values are higher than a threshold value (approximately $N_{60} = 20$ for sandy soil and $N_{60} = 15$ for fine-grained soil). However, on the average, the measured Vs by suspension logging testing seems to be slightly larger than the measurements by cross-hole seismic testing when the SPT-N values are small. In view of the coefficient of determination (R^2), the cross-hole seismic testing in this study has the highest R^2; the suspension logging testing ranks the second highest



(a) Cross-hole seismic testing



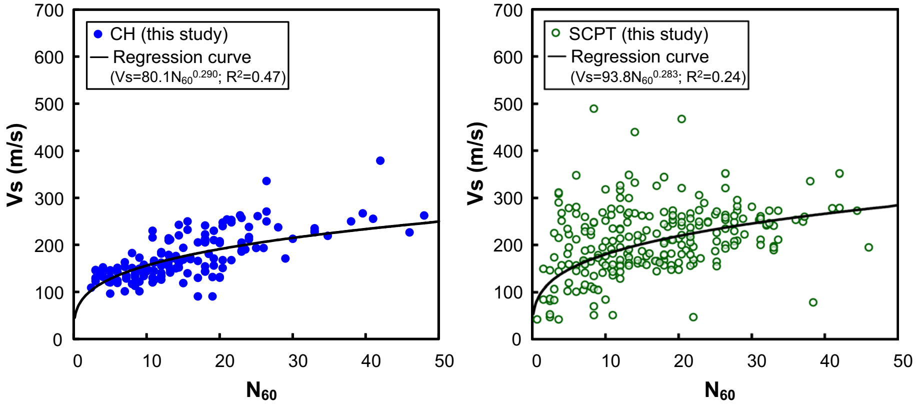
(b) Seismic cone penetrometer **(c)** Suspension logging testing

Fig. 4 The database established by this study

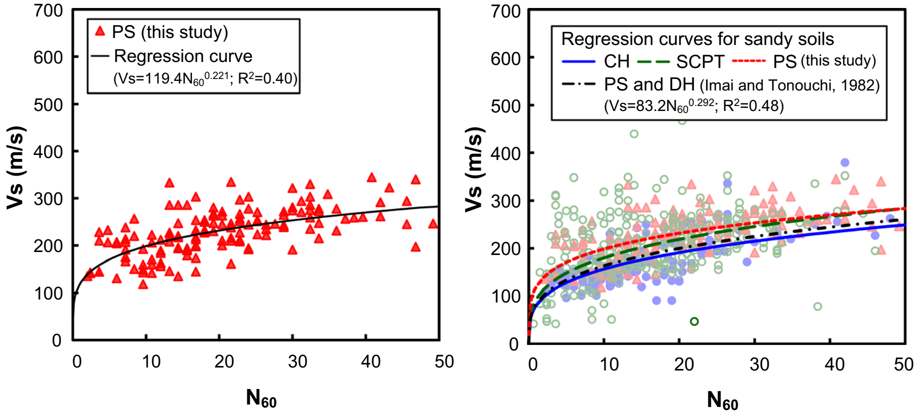
Table 4 Details of the datasets from this study

Category	No. of data	Vs measurement method	Soil type	USCS
1	156	Cross-hole logging	Sandy soil	SC, SM, SP, SW
2	240	SCPT		
3	142	Suspension logging		
4	149	Cross-hole logging	Fine-grained soil	CL, CH, ML, CL-ML
5	330	SCPT		
6	129	Suspension logging		

R^2; the data pairs by SCPT and the referred N-value are the most scattered and has the lowest R^2, which is probably due to the spatially varied soil conditions between the SCPT and SPT.



(a) Cross-hole seismic testing **(b)** Seismic cone penetrometer

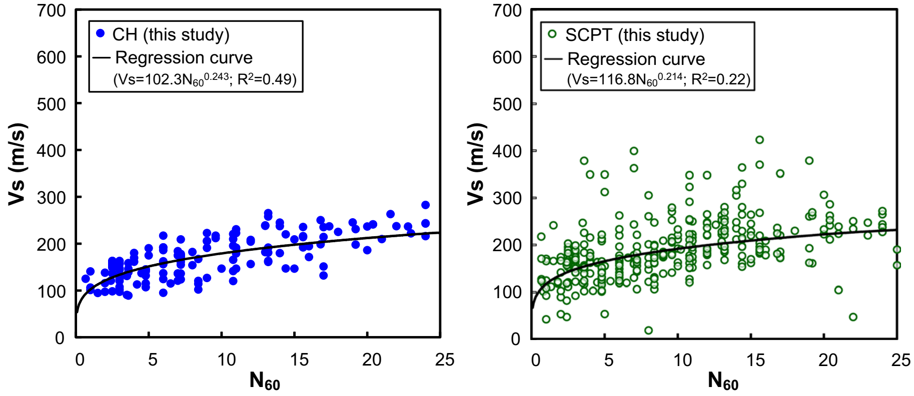


(c) Suspension logging testing **(d)** all data with regression curves

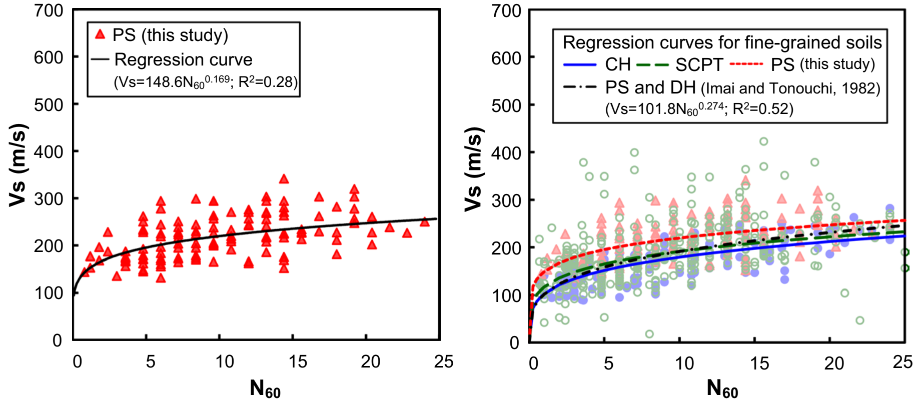
Fig. 5 Vs versus N_{60} and correlation equations for the sandy soil group

3.3 A comparison with the Japanese database

In Japan, the measurement of shear wave velocity and the studies for establishing the relationship between the N-value and Vs have been ongoing since the 1960s (Kanai 1966; Shibata 1970; Ohba and Toriuma 1970; Ohsaki and Iwasaki 1973; JSSMFE 1981; Imai and Tonouchi 1982). Among these studies, the database provided by Mr. Tsuneo Imai and the associated regression results recorded by JSSMFE (1981) have been commonly referred by the Japanese Road Association (JRA) for many decades. The database has 183 datasets with information on clayey (fine-grained) soils, and 151 datasets with information on sandy soils in alluvium. The regression equations, with a little modification to the regressed parameters for the purpose of practical use, were adopted by the JRA (2002) and implemented in their design codes. The database was updated by Imai and Tonouchi (1982), and the number of the datasets of clayey (fine-grained) soils became 325, and the number of the datasets of sandy soils became 294. The database established by Imai and Tonouchi (1982) (hereinafter referred to as IT database) are mainly measured by downhole seismic testing

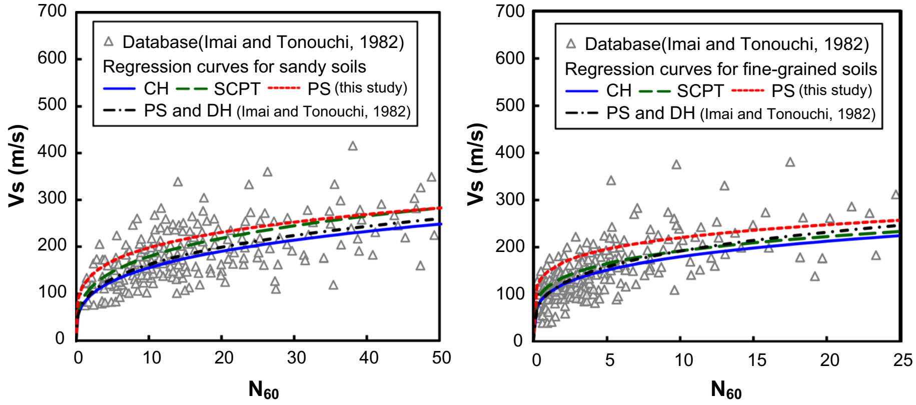


(a) Cross-hole seismic testing **(b)** Seismic cone penetrometer



(c) Suspension logging testing **(d)** all data with regression curves

Fig. 6 Vs versus N_{60} and correlation equations for the fine-grained soil group



(a) Sandy soil group **(b)** Fine-grained soil group

Fig. 7 The databases of Imai and Tonouchi (1982) as well as regression curves and suspension logging testing in alluvium. It is believed that the updated database should have a certain degree of reliability and could be a reference to compare with the database used in this study. Figure 7 displays the Vs versus N_{60}-value distribution of the IT database. Note that the information of the SPT energy ratio, as well as the hammer type, are not available in Imai and Tonouchi (1982). According to Nishizawa et al. (1980), the energy ratio in Japanese hammer systems is from 63 to 72% for rope-cathead system and from 80 to 90% for automatic hammer system. An energy ratio of 72% was assumed, which is about average of the rope-cathead and automatic hammer systems in Japan, and the N-values of the data pairs in IT database were converted to N_{60}-values accordingly. Besides, the data pairs with N_{60} larger than 50 in sandy soil group and 25 in fine-grained soil group do not show in the figure. From Figs. 5, 6, and 7, it can be seen that the data pairs collected from the SCPT and referred N-value are relatively scattered. Other than that, the Vs measurement results among the discussed methods are comparable. The difference among them would be discussed more in following section.

4 SPT-based Vs correlations

Standard Penetration Test (SPT) has historically been the most widely used in situ geotechnical test throughout the world. In order to easily estimate shear wave velocity of soils by SPT-N value, many researchers have studied the relationship between the Vs and SPT-N value. From Figs. 5 and 6, it is obvious that different Vs measurement methods can give quite different values of Vs, but few studies addressed this difference and investigated the rationale of Vs measurements in alluvium. The Vs difference caused by measurement methods also results in different Vs versus N-value correlation equations. To address this, the study used the above built database and separately established correlation equations for each of the dataset categories. The relationship of Vs versus N-value follows the form of Eq. (4):

$$\mathrm{Vs} = \mathrm{a}\, \mathrm{N}_{60}^{\mathrm{b}} \tag{4}$$

where “a” and “b” are the parameters to be determined by the regression analysis. The parameter “a” is a scaling factor, moving the values of $\mathrm{N}_{60}^{\mathrm{b}}$ up or down, and the parameter “b”, called the power, determines the increasing rate of Vs as N value increases.

Note that these datasets typically contain a significant amount of scatter in the measurements (as evident in Figs. 5 and 6). To develop a better correlation, the “LINEST” function of Microsoft Excel was used to perform a best fit of the data in regression analysis. The coefficients of determination (R^2) were used to assess the strength of the relationships between variables. Higher correlation coefficients indicate greater correlation between two variables. Perfect correlation between variables would result in a “R^2” of 1.0. Further discussions of the regressed correlation equations, as well as the comparison with Japanese equations, are presented in the following sections.

4.1 Sandy soils

A summary of Vs versus N_{60}-value correlation equations for sandy soils, as well as the equations from IT database of sandy soils (Imai and Tonouchi 1982), is presented in Table 5a. In view of the coefficient of determination (R^2) shown in Fig. 5, the cross-hole

Table 5 Vs versus N_{60}-value correlation equations

Category	$Vs = aN_{60}^{b}$		R^2	Vs measurement method
	a	b		
(a) Sandy soils				
1	80.1	0.290	0.47	Cross-hole seismic testing
2	93.8	0.283	0.24	Seismic cone penetrometer
3	119.4	0.221	0.40	Suspension logging testing
IT[a]	83.2	0.292	0.48	Suspension logging testing and downhole seismic testing
(b) Fine-grained soils				
4	102.3	0.243	0.49	Cross-hole seismic testing
5	116.8	0.214	0.22	Seismic cone penetrometer
6	148.6	0.169	0.28	Suspension logging testing
IT[a]	101.8	0.274	0.52	Suspension logging testing and downhole seismic testing
(c) All soils				
7	110.9	0.227	0.28	–

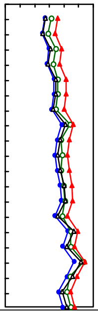
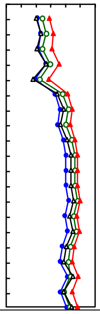
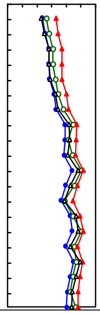
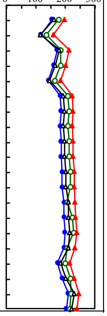
[a] The “a” and “b” regression parameters and R^2 are from Imai and Tonouchi (1982)

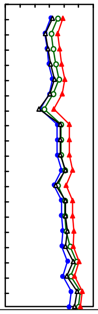
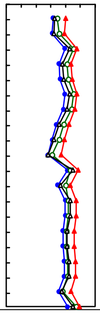
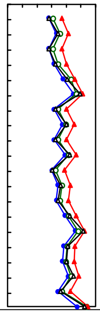
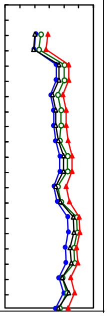
seismic testing in this study and IT database have the highest R^2, which demonstrates the reliability of the measurements of the shear wave velocity; the suspension logging testing in this study ranks the second most R^2; the data pairs by SCPT and the referred N-value are the most scattered. On the basis of the similar Vs measurement method, the results measured by the suspension logging testing in this study are still much scattered than those in IT database. From the regression results based on all analyzed categories, basically, it can be seen that when parameter “a” is larger, parameter “b” will be smaller. Figure 5d shows the yielded regression curves, as well as the result by Imai and Tonouchi (1982). All regression curves are comparable. The results show that the predicted Vs (the red dotted curve in Fig. 5d) based on the data pairs of suspension logging testing is the least conservative. The one based on the data pairs measured by SCPT is the second. In contrast, the predicted Vs based on the regression curves by the data pairs of cross-hole seismic testing (the blue curve in Fig. 5d) are the most conservative, which is very close to the one derived by Imai and Tonouchi (1982).

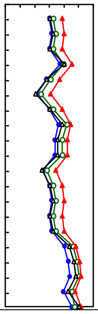
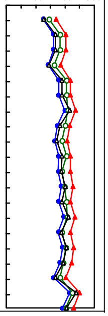
4.2 Fine-grained soils

A summary of Vs versus N_{60}-value correlation equations for fine-grained soils, as well as the equations from IT database of cohesive soils (Imai and Tonouchi 1982), is presented in Table 5b. In view of the coefficient of determination (R^2) shown in Fig. 6, the data pairs by cross-hole seismic testing in this study and those of IT database have the highest R^2, which could demonstrate the better reliability of the Vs measurements; the R^2 from the database of the suspension logging testing in this study ranks the second; the data pairs by SCPT and the referred N-value are the most scatter. The trend of the R^2 is similar to that of sandy soils, except with a lower R^2 in cohesive soils than that of sandy soils for the case

Table 6 The predicted Vs for each site

	CHY004			CHY012			CHY016			CHY027		
Depth (m)	USCS	SPT-N_{60} (blow)	Predicted Vs (m/s) 0 100 200 300	USCS	SPT-N_{60} (blow)	Predicted Vs (m/s) 0 100 200 300	USCS	SPT-N_{60} (blow)	Predicted Vs (m/s) 0 100 200 300	USCS	SPT-N_{60} (blow)	Predicted Vs (m/s) 0 100 200 300
1.5	SM	6		SM	2		ML	2		SW-SM	10	
3.0	SM	5		SM	4		ML	4		SM	4	
4.5	SP-SM	8		CL	1		CL	4		CH	8	
6.0	SM	7		ML	3		CL-ML	4		SM	11	
7.5	ML	7		CL	1		SM	7		SW-SM	7	
9.0	ML	7		SM	12		ML	6		SW-SM	17	
10.5	ML	6		SM	17		SM	12		SM	18	
12.0	SP-SM	20		SM	14		SW-SM	22		SM	16	
13.5	ML	10		SM	20		ML	14		SM	18	
15.0	SM	13		SM	24		SM	20		SM	18	
16.5	ML	10		SP-SM	24		SM	32		SM	19	
18.0	ML	12		SP-SM	24		SM	23		SM	19	
19.5	ML	13		SM	28		ML	11		ML	14	
21.0	SM	13		SM	23		ML	20		SM	22	
22.5	ML	20		SM	26		SM	32		SM	23	
24.0	SW-SM	22		SM	19		SM	23		ML	14	
25.5	SM	41		SM	17		ML	25		SM	14	
27.0	ML	19		ML	18		ML	20		SM	19	
28.5	SM	17		CL	11		ML	17		ML	19	
30.0	SM	22		ML	17		SM	24		ML	17	

	CHY031			CHY044			CHY049			CHY059		
Depth (m)	USCS	SPT-N_{60} (blow)	Predicted Vs (m/s) 0 100 200 300	USCS	SPT-N_{60} (blow)	Predicted Vs (m/s) 0 100 200 300	USCS	SPT-N_{60} (blow)	Predicted Vs (m/s) 0 100 200 300	USCS	SPT-N_{60} (blow)	Predicted Vs (m/s) 0 100 200 300
1.5	SP-SM	10		ML	6		CL	4				
3.0	SW-SM	6		SP-SM	10		CL	7		SM	2	
4.5	SM	7		SP-SM	23		ML	4		SM	2	
6.0	SM	8		SP-SM	16		CH	6		SM	14	
7.5	SW-SM	11		SM	17		SM	19		SM	14	
9.0	ML	5		SP-SM	23		ML	25		SP-SM	10	
10.5	ML	2		SM	20		CL	6		SM	12	
12.0	CL	10		SM	13		ML	12		SM	12	
13.5	ML	10		SM	10		CL	6		ML	8	
15.0	CL	10		CL	4		ML	14		SM	18	
16.5	ML	13		CL	18		CL	5		SM	18	
18.0	CL	7		SM	14		CL	8		ML	7	
19.5	ML	13		ML	16		CL	7		ML	10	
21.0	CL	13		CL	16		CL	14		SP-SM	29	
22.5	CL-ML	14		ML	13		ML	29		SM	30	
24.0	SM	20		CL	13		CL	13		SM	25	
25.5	SM	29		ML	14		CH	12		SM	26	
27.0	SM	22		ML	14		ML	18		ML	11	
28.5	SM	35		CL-ML	10		CL	8		ML	16	
30.0	SM	31		SM	26		SM	42		CL	8	

	CHY066			CHY112		
Depth (m)	USCS	SPT-N_{60} (blow)	Predicted Vs (m/s) 0 100 200 300	USCS	SPT-N_{60} (blow)	Predicted Vs (m/s) 0 100 200 300
1.5	CL	5		SM	5	
3.0	CL-ML	6		SM	11	
4.5	CL	5		SM	11	
6.0	CL	12		SW-SM	7	
7.5	CL	4		SM	16	
9.0	CL	1		SW-SM	16	
10.5	ML	5		ML	16	
12.0	SM	17		SM	14	
13.5	SM	13		SW-SM	12	
15.0	SM	13		SM	16	
16.5	CL	2		CL	10	
18.0	CL	5		ML	12	
19.5	CL	6		SM	16	
21.0	CL	5		ML	14	
22.5	ML	6		ML	10	
24.0	SM	24		ML	13	
25.5	SM	30		ML	11	
27.0	SM	32		SM	11	
28.5	SM	23		ML	22	
30.0	ML	26		ML	13	

- ● Predicted by the regression curves based on the datasets from cross-hole seismic testing
- ▲ Predicted by the regression curves based on the datasets from suspension logging testing
- ○ Predicted by the regression curves based on the datasets from SCPT
- △ Predicted by the Japanese regression curves testing

of suspension logging testing. It is interesting that a lower R^2 occurs when applying the suspension logging seismic testing to measure the shear wave velocity of fine-grained soils in this study. The reason will be discussed in the following section. From the regression results for all analyzed categories, a larger "a" parameter, will have a smaller "b" parameter. Figure 6d shows the regression curves as well as the result by Imai and Tonouchi (1982). All regression curves are basically comparable. From the figure, most of the predicted Vs from regression curve by the data pairs of cross-hole seismic testing is relatively conservative (the blue curve in Fig. 6d). However, the predicted Vs by the regression curve from the data pairs of suspension logging testing (the red dotted curve in Fig. 6d) is obviously higher than the other regression curves whereas the IT database is also mainly based on the suspension logging testing. The other two regression curves fall between.

4.3 All soils

The Vs versus N_{60}-value correlation equations for all soils used in this study is also presented in Table 5c. The parameters of “a” and “b” are 110.9 and 0.227, respectively. The coefficient of determination (R^2) is 0.28. The engineers can use the equation to evaluate Vs of a soil layer if only the information of SPT-N value is available. However, it should be noted that the prediction would be definitely more uncertain than the one with the information of soil type.

4.4 Discussion

Among the measurement results in this study, cross-hole seismic testing is the most reliable method in view of the evaluation based on R-square. This result also agrees with comments by Andrus et al. (2004) in Table 2. In comparison with the results by Imai and Tonouchi (1982), the results between two are quite comparable in view of the evaluated R^2 and the distribution of the data pairs. The data pairs by SCPT and the referred N-value show the most scatter. This may be the result of differing locations of the Vs and SPT measurements. Even so, the regression results based on these data pairs are still comparable with the ones based on the database of the cross-hole seismic testing. However, the SCPT measured Vs seems to be slightly higher than the one from cross-hole seismic testing.

As for the suspension logging testing, it is obvious that the regression curves based on the data measured by it in this study and in Imai and Tonouchi (1982) are different. The distribution of the data pairs is more scattered and the regression curve is non-conservative than the one proposed by Imai and Tonouchi (1982). A possible reason may be due to the difference in the preparation of the testing borehole. In Taiwan, the borehole for suspension logging has to be cased before measurement to avoid borehole collapse in alluvium sites. Based on the consultation with the Japanese engineers, the comments on the installation of the PVC casing for suspension logging testing are not totally consistent. Some suggest that the effect of the installation of the PVC casing is slight. In contrast, some think the installation of the PVC casing does affect the measurement results and should not be used as much as possible in order to derive better measurement. The consensus is that, in soft ground, the stability of the borehole should be evaluated first and the installation of PVC casing may be necessary in order not to stick the apparatus in the borehole. Once a borehole is cased, it is necessary to fill the gap space between ground formation and casing tube to ensure seismic waves propagate directly into the sensor without pollution of tube waves. Therefore, the borehole is always cased, and the PVC casing must be properly installed and grouted (see Fig. 8). Note that the shear wave propagation in suspension logging testing travels in the vertical direction, which means that the seismic wave may travel through grouted soils. Theoretically, the grout material should be as soft as the soils surrounding the borehole. In practices, it is really difficult to control the hardness of the grout accurately. In most cases, the hardness of grout is always greater than that of soft formations (i.e., lower N-value condition). This could cause overestimation of the shear wave velocity. Indirect evidence of the possible overestimation of Vs by the suspension logging test may be found by comparing the regression curves in Figs. 5 and 6 with the data pairs based on the SCPT. In SCPT, the travel path of the seismic wave is also in vertical direction, but it does not require the installation of the PVC casing and grouting. The record of the use of any casing in suspension logging testing is very important in order to let the designer make a reasonable

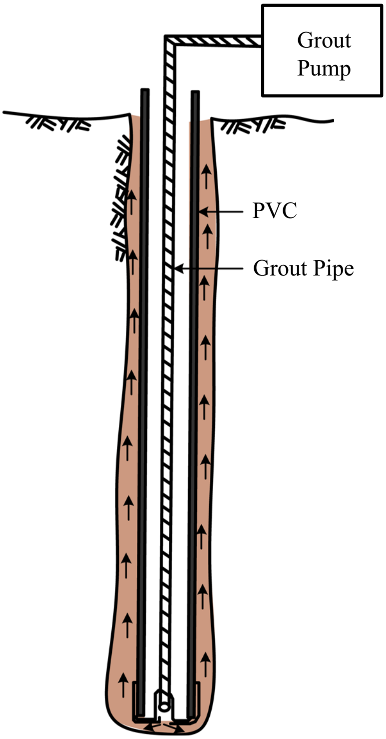


Fig. 8 The installation of the PVC casing and grouting before conducting suspension logging testing in Taiwan

engineering judgement. It is doubtful whether the problem of Vs overestimation also exists when conducting cross-hole seismic testing, where casing and the grouting of the testing boreholes are also required. Fortunately, the possible overestimation of Vs due to the effect of soil improvement could be largely reduced since the horizontal travel path of the shear wave propagation between the two testing boreholes (Fig. 2) is much longer than the grout-effected zones.

Other than the above possible reasons, it should be noted that Sites A to K only had Vs measurements by cross-hole seismic testing and SCPT, which may be the reason that the regression curves based on the two Vs measurement methods were comparable. In contrast, Sites L to Y only had the Vs measurements by suspension logging testing. In the database of this study, none of the sites included the Vs measurements based on the three methods of interest. The variation of site characteristics may be another reason that the regression curves based on the suspension logging testing were different from the others.

5 Case study

In this case study, the influence of different regressed Vs-N curves deduced by different measurement methods on site classification will be demonstrated. Totally, four sets of regression curves were used. Three sets of regression curves were established by cross-hole logging, SCPT, and suspension logging respectively in this study and the other one set was directly cited from Imai and Tonouchi (1982). Each set had two regression curves, one for sandy soils and the other for fine-grained soils. In this demonstration, 10 sites located at the alluvium in central and south Taiwan were selected. They are sites M, N, O, R, S, U, V, W, X, and Y which are shown in Fig. 3 and denoted with new symbols as CHY004, CHY012, CHY016, CHY027, CHY031, CHY044, CHY049, CHY059, CHY066, and CHY112, accordingly. The Vs profile of each site was evaluated by SPT-N according to the 4 sets of the Vs-N regression curves. Table 6 shows the SPT results from the boreholes of the 10 sites, and the predicted Vs based on different sets of regression curves. With the shear wave velocities along the borehole, Vs30 could then be calculated according to Eq. (1), and the site classification could be determined by Table 2. The Vs30 of all sites are shown in Fig. 9. It can be found that all the 10 sites are classified into Site Class III by regression curves from cross-hole logging and Site Class II by regression curves from SCPT and suspension logging. If using regression curves suggested by Imai and Tonouchi (1982), four sites are classified into Site Class III and six sites are Site Class II. Therefore, it can be concluded that the influence of Vs measurement methods on site classification is at most one class difference. Following the above results, the subsequent influence on the design response spectra can be evaluated by comparing the site coefficients of F_a and F_v corresponding to the two evaluated site classes (Site Classes II and III). For a site located in the seismic region with $S_s = 0.6$ and $S_1 = 0.35$ in Taiwan, for example, the site coefficients of F_a and F_v at the Class II site are 1.1 and 1.4 respectively while the F_a and F_v at the Site Class III are 1.2 and 1.7 respectively, according to MOI (2001). The ratios of F_a and F_v between the Site Class II and III are about 1.09 and 1.21 respectively. This means the design seismic force acting on a building located in Class III site would be larger than that of the same building located in Class II site by a difference of 9 ~ 21% which depends on the period of the building considered.

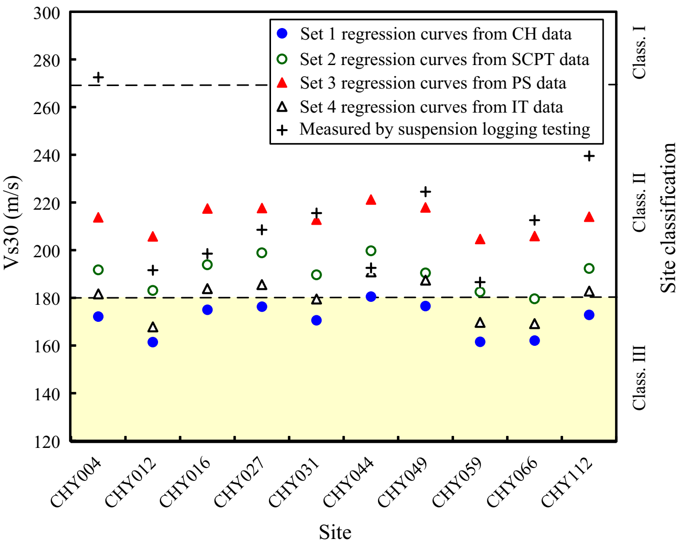


Fig. 9 The predicted Vs30 for each site

6 Conclusion

1. The established Vs-N database by cross-hole logging, SCPT, and suspension logging is believed to be reliable and provide a good reference for the relevant research work.
2. The discrepancies of the Vs-N correlations based on the database produced by different methods are found to be about tens of meters per second. The influence of Vs measurement methods on site classification is at most one class difference.
3. The predicted results of the site classification did vary if different sets of regression curves were adopted. The curves regressed from the datasets of cross-hole seismic testing are the most conservative in determining design seismic forces. Care must be taken when using less conservative regression curves by other measurement methods while conducting design work.
4. From the comparison study, it was found that the measured Vs by suspension logging testing were non-conservative than the other methods for shallow soft alluviums. This is because seismic waves produced by the suspension logging travel vertically along the surrounding disturbed region of borehole. The grouting between PVC case and borehole wall may affect the measurement results significantly.

Acknowledgements In establishing the framework of this paper, valuable discussion with Dr. Chun-Hsiang Kuo of NCREE, Mr. Takafumi Kameda of ATK cooperation, and Miss Sayoko Maruyama of OYO cooperation were of great help. The assistance of Dr. Motoi Kawanishi of ATK in collecting the Japanese literature provided the authors a good reference. The authors wish to express their sincere thanks to them.

References

Akin MK, Kramer SL, Topal T (2011) Empirical correlations of shear wave velocity (Vs) and penetration resistance (SPT-N) for different soils in an earthquake prone area (Erbaa-Turkey). Eng Geol 119:1–17

Anbazhagan P, Sitharam TG (2006) Evaluation of dynamic properties and ground profiles using MASW: correlation between Vs and N60. In: 13th symposium on earthquake engineering indian institute of technology. Roorkee, pp 1–10

Anbazhagan P, Uday A, Moustafa SSR, Al-Arifi NSN (2016) Correlation of densities with shear wave velocities and SPT N values. J Geophys Eng 13:320–341

Andrus RD, Stokoe KH, Juang CH (2004) Guide for shear-wave-based liquefaction potential evaluation. Earthq Spectra 20(2):285–308

Building Seismic Safety Council (BSSC) (1985) NEHRP recommended provisions for seismic regulations for new buildings and other structures, FEMA 95. Federal Emergency Management Agency, Washington, D.C.

Building Seismic Safety Council (BSSC) (1988) NEHRP recommended provisions for seismic regulations for new buildings and other structures, FEMA 95. Federal Emergency Management Agency, Washington, D.C.

Building Seismic Safety Council (BSSC) (1991) NEHRP recommended provisions for seismic regulations for new buildings and other structures, FEMA 222/223. Federal Emergency Management Agency, Washington, D.C.

Building Seismic Safety Council (BSSC) (2003) NEHRP recommended provisions and commentary for seismic regulations for new buildings and other structures, FEMA 450. Federal Emergency Management Agency, Washington, D.C.

Center for Earthquake Engineering Research National Taiwan University (CEERNTA) (2000) A study of engineering properties of the ash in the chimney areas of the units 9 and 10 in the Taichung thermal power plant. Research report. Taiwan Power Company (**in Chinese**)

Chatterjee K, Choudhury D (2013) Variations in shear wave velocity and soil site class in Kolkata city using regression and sensitivity analysis. Nat Hazards 69(3):2057–2082

Construction and Planning Agency, MOI (2011) Seismic design specifications and commentary of buildings (**in Chinese**)

Dobry R, Borcherdt RD, Crouse CB, Idriss IM, Joyner WB, Martin GR, Power MS, Rinne EE, Seed RB (2000) New site coefficients and site classification system used in recent building seismic code provisions. Earthq Spectra 16(1):41–67

Garofalo F, Foti S, Hollender F, Bard PY, Cornou C, Cox BR, Dechamp A, Ohrnberger M, Perron V, Sicilia D, Teague D, Vergniault C (2016) InterPACIFIC project: comparison of invasive and non-invasive methods for seismic site characterization. Part II: inter-comparison between surface-wave and borehole methods. Soil Dyn Earthq Eng 82:241–254

Hanumantharao C, Ramana GV (2008) Dynamic soil properties for microzonation of Delhi, India. J Earth Syst Sci 117(Supplement 2):719–730

Hasancebi N, Ulusay R (2007) Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments. Bull Eng Geol Environ 66(2):203–213

Hwang JH (1997) The dynamic properties of Keelung river clay. Research report. National Science Council, NSC 87-2621-P-008-009 (**in Chinese**)

Hwang JH, Lee CJ, Hwang FK (1998) Soil liquefaction evaluation and countermeasures at the intersected area of Southern Second Freeway and Hsinhwa fault. Research report. National Expressay Engineering Bureau (MOTC) (**in Chinese**)

Hwang JH, Chang CT, Chou KT, Yu MS, Jean WY (2002) The suitability of the simplified methods used for evaluating soil liquefaction in Taiwan using the case histories of the Chi-Chi earthquake. Research report. National Expressway Engineering Bureau (MOTC) (**in Chinese**)

Imai T, Tonouchi K (1982) Correlation of N-value with S-wave velocity and shear modulus and its application. Found Eng 70–76 (**in Japanese**)

Imai T, Yoshimura Y (1975) The relation of mechanical properties of soils to P and S-wave velocities for ground in Japan. Technical Note. OYO Corporation

Ishihara K (1996) Soil behavior in earthquake geotechnics. Oxford University Press Inc., New York

Jafari MK, Shafiee A, Ramzkhah A (2002) Dynamic properties of the fine grained soils in south of Tehran. J Seismol Earthq Eng 4(1):25–35

Japan Road Association (JRA) (2002) Specification for highway bridges, Part V Seismic Design

Japanese Society of Soil Mechanics and Foundation Engineering (JSSMFE) (1981) Geophysical investigation for foundation soil (**in Japanese**)

Jhinkwan H, Jain PK (2016) Prediction of shear wave velocity using SPT-N value. Intern J Curr Eng Sci Res (IJCESR) 3(7):28–36

Kanai K (1966) Observation of microtremors, XI: Matsushiro earthquake swarm areas. Bull. Earthq. Res. Inst., vol. XLIV, Part 3, University of Tokyo, Tokyo, Japan

Kirar B, Maheshwari BK, Muley P (2016) Correlation between shear wave velocity (Vs) and SPT resistance (N) for Roorkee region. Int J Geosynth Ground Eng 2(1):9

Kumar A, Anbazhagan P, Sitharam TG (2010) Shear wave velocity profiling for Lucknow urban centre using seismic refraction survey. In: Indian Geotechnical Conference, GEO. trendz. pp 167–170

Kuo CH, Wen KL, Hsieh HH, Lin CM, Chang TM, Kuo KW (2012) Site classification and Vs30 estimation of free-field TSMIP stations using the logging data of EGDT. Eng Geol 129–130:68–75

L'Heureux JS, Long M (2017) Relationship between shear-wave velocity and geotechnical parameters for Norwegian clays. J Geotech Geoenviron Eng ASCE 163(6):04017013

Maheswari RU, Boominathan A, Dodagoudar GR (2010) Use of surface waves in statistical correlations of shear wave velocity and penetration resistance of Chennai soils. Geotech Geol Eng 28(2):119–137

Marto A, Soon TC, Kasim F, Suhatril M (2013) A correlation of shear wave velocity and standard penetration resistance. Electron J Geotech Eng (EJGE) 18:463–471

Moh and Associates, Inc. (MAA) (2000) Soil liquefaction evaluation and countermeasures: phase I (Yuanlin township, Dacun Township, and Shetou Township of Changhua County). Research report. National Science Council (**in Chinese**)

National Center for Research on Earthquake Engineering (NCREE) (2016a) Report of the seismic cone penetration test (SCPT) in the Tainan area after the Meinong earthquake. Research report. NCREE (**in Chinese**)

National Center for Research on Earthquake Engineering (NCREE) (2016b) Site investigation of the Tainan liquefied sites after the Meinong earthquake. Research report. NCREE (**in Chinese**)

National Center for Research on Earthquake Engineering (NCREE) (2016c) Geological boring at the Tainan liquefied sites after the Meinong earthquake. Research report. NCREE (**in Chinese**)

National Central University (NCU) (2010) Laboratory and in situ test report of the ash materials before and after the improvement of the sand compaction pile in ash pond of the Taichung thermal power plant. Research report. Taiwan Power Company (**in Chinese**)

Nigbor RL, Imai T (1994) The suspension P-S velocity logging method. In: Proceedings of XIII international conference on soil mechanics and foundation engineering, 5–10 Jan 1994, New Delhi, India

NishizawaY, Fuyuki S, Uto K (1980) In situ tests and efficiency concerning SPT. In: Proceedings of sounding symposium, JSSMFE. pp 83–92 (**in Japanese**)

Ohba S, Toriuma I (1970) Research on vibrational characteristics of soil deposits in Osaka, Part 2, on velocities of wave propagation and predominant periods of soil deposits, Abstracts of Technical Meeting of Architectural Institute of Japan

Ohsaki Y, Iwasaki R (1973) On dynamic shear moduli and Poisson's ratio of soil deposits. Soil Found 13(4):61–73

Seed HB, Ugas C, Lysmer J (1976) Site-dependent spectra for earthquake-resistant design. Bull Seism Soc Am 66(1):221–244

Shibata T (1970) The relationship between the N-value and S-wave velocity in the soil layer, Disaster Prevention Research Laboratory, Kyoto University, Kyoto, Japan

Sino Geotechnology, Inc. (2000–2008) Record report of drilling and investigation at strong motion stations, National Center for Research on Earthquake Engineering (**in Chinese**)

Sinotech Engineering Consultants (1993) Basic design of Taiwan High Speed Rail: The study of soil liquefaction potential evaluations. Research report. Preparatory Office of High Speed Rail (**in Chinese**)

Sinotech Engineering Consultants (1996) The development of the Changhua coastal industrial park: Geological drilling and test in 1995. Research report. Industrial Development Bureau (MOEA) (**in Chinese**)

Sykora DW (1987) Examination of existing shear wave velocity and shear modulus correlations in soils, Department of the Army, Waterways Experiment Station, Corps of Engineers, Miscellaneous Paper GL-87-22

Sykora DW, Koester PJ (1988) Correlations between dynamic shear resistance and standard penetration resistance in soils. Earthq Eng Soil Dyn 2:389–404

Sykora DE, Stokoe KH (1983) Correlations of in situ measurements in sands of shear wave velocity. Soil Dyn Earthq Eng 20:125–136

Taiwan Construction Research Institute (TCRI) (1997) Optimization of the bridge foundations of high speed rail: Report on geotechnical investigation at Chiayi test site. Research report. Bureau of High Speed Rail, MOTC, No. 2-0-86-25-02-165 (**in Chinese**)

Terzaghi K, Peck R (1967) Soil mechanics in engineering practice, 2nd edn. Wiley, New York

Tsiambaos G, Sabatakakis N (2011) Empirical estimation of shear wave velocity from in situ tests on soil formations in Greece. Bull Eng Geol Environ 70(2):291–297

Ulugergerli UE, Uyanik O (2007) Statistical correlations between seismic wave velocities and SPT blow counts and the relative density of soils. J Test Eval 35(2):1–5

Unal D (2009) Statistical correlations of shear wave velocity and penetration resistance for soils. J Geophys Eng 6(1):61–72

Wair BR, DeJong JT, Shantz T (2012) Guidelines for estimation of shear wave velocity profiles. Pacific Earthquake Engineering Reserach Center. Berkeley, CA

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.