전단파속도와 지반공학적 현장 관입시험 자료의 상관관계 도출

Deduction of Correlations between Shear Wave Velocity and Geotechnical In-situ Penetration Test Data

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국문 요약 >> 다양한 탄성파 시험으로부터 획득할 수 있는 전단파속도(V_S)는 주로 지진공학 분야에서의 내진 설계 및 내진 성능 평가를 위한 대표적 지반 동적 특성으로 강조되어 왔다. 일반적인 지반공학적 부지 조사 기법의 지반지진공학적 활용을 목적으로, 표준관입 시험(SPT)과 피에조콘관입시험(CPTu)을 국내 여러 부지들을 대상으로 다양한 시추공 탄성파시험과 함께 수행하였다. 본 연구에서는 현장 시험 자료들의 통계학적 모델링을 통해 전단파속도와 표준관입시험의 타격수(N 값) 및 선단저항력(q_t), 주면마찰력(f_s)과 간극수압계수(B_q)로 구성되는 피에조콘관입 자료 간의 상관관계를 도출하고 전단파속도 결정을 위한 경험적 방법으로 제안하였다. 비록 일반적인 지반공학적 관입시험과 시추공 탄성파시험의 대상 변형률 수준이 상이하다 할지라도, 본 연구에서 제안된 상관관계들은 국내 토사 지층의 예비적 전단파속도 산정에 활용될 수 있을 것으로 보인다.

주요어 전단파속도, 피에조콘관입 시험, 표준관입 시험, 시추공 탄성파 시험, 현장 관입 시험

ABSTRACT >> Shear wave velocity (V_S), which can be obtained using various seismic tests, has been emphasized as representative geotechnical dynamic characteristic mainly for seismic design and seismic performance evaluation in the engineering field. For the application of conventional geotechnical site investigation techniques to geotechnical earthquake engineering, standard penetration tests (SPT) and piezocone penetration tests (CPTu) together with a variety of borehole seismic tests were performed at many sites in Korea. Through statistical modeling of the in-situ testing data, in this study, the correlations between V_S and geotechnical in-situ penetrating data such as blow counts (N value) from SPT and piezocone penetrating data such as tip resistance (q_t), sleevefriction (f_s), and pore pressure ratio (B_q) were deduced and were suggested as an empirical method to determine V_S. Despite the incompatible strain levels of the conventional geotechnical penetration tests and the borehole seismic tests, it is shown that the suggested correlations in this study are applicable to the preliminary estimation of V_S for Korean soil layers.

Key words shear wave velocity, piezocone penetration test, standard penetration test, borehole seismic test, in-situ penetration test

1. Introduction

As the exploration geophysics has been advanced in the technical aspect and recognized to be useful in the construction practices, a variety of geophysical methods have been widely applied to civil engineering. Among various disciplines of civil engineering, geotechnical engineering includes in-situ site investigations for determining various subsurface soil properties. In particular, seismic methods such as borehole seismic tests are recently applied to obtain dynamic soil properties, to require primarily for seismic design and seismic performance evaluation. From the geotechnical perspective, shear wave velocity (V_S), which were usually emphasized as a seismic design parameter could be determined only from in-situ seismic tests.[(1),(2)]

A number of in-situ geotechnical tests as well as the recent seismic tests for the V_S profile have been performed

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본 논문에 대한 토의를 2008년 10월 31일까지 학회로 보내 주시면 그 결과를 게재하겠습니다.

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to evaluate various soil characteristics including static soil properties such as nonlinear stiffness, strength, initial stress state, anisotropy, permeability, drainage characteristics and rheological behavior. The standard penetration test (SPT) and the piezocone penetration test (CPTu or PCPT) can be regarded as the most well-known geotechnical in-situ tests. Both tests have been conducted in engineering practices for a long time and their data have been vastly accumulated, especially in Korea.

As a part of the utilization of testing data from the SPT and CPTu in geotechnical earthquake engineering related to the seismic design and seismic performance evaluation, the SPTs were conducted together with various borehole seismic tests such as crosshole, downhole, and uphole seismic tests, and the seismic piezocone penetration tests (SCPTu), which are hybrid testing method coupling the CPTu with the downhole seismic test, were carried out in Korea. *N* values from the SPT and the reading data during penetration including tip resistance (q_t), sleeve friction (f_s) and excess pore pressure (u) from the CPTu are obtained. In this study, these resultant data from two conventional geotechnical in-situ tests are correlated with the V_S values from borehole seismic tests and empirical forms to estimate V_S values are proposed.

2. In-situ Tests for This Study

2.1 Geotechnical In-situ Tests

Since the beginning of geotechnical engineering that involves the interrelationship between geologic environment and the works of humans, the geotechnical in-situ tests for site characterization have been emphasized and conducted by means of a variety of techniques. Nowadays, a good number of different geotechnical in-situ tests are available for site investigation in soil deposits with the most common being the SPT, CPTu (also CPT), flat dilatometer test (DMT), pressuremeter test (PMT) and vane shear test (VST).[(3)] Besides these geotechnical in-situ investigation tests, the recent site investigation program could include various geophysical surveys. Among the common in-situ tests, the most widely used dynamic and static penetration testing methods are the SPT and the CPTu, respectively, which are adopted in this study.

The standard penetration test (SPT) detailed in ASTM D 1586[(4)] has been widely conducted to determine the soil conditions and also obtain the disturbed soil samples for many years all over the world. One reason why the SPT is so popular is that many correlations between SPT blow counts (*N* value) and soil properties required for geotechnical design have been proposed and used. Nevertheless, the correlations reflecting the local soil characteristics in Korea have been rarely suggested particularly for the empirical estimation of shear wave velocity (V_S).

The piezocone penetration test (CPTu) is quickly becoming the most popular type of in-situ test because it is able to provide an essentially continuous indication of soil consistency and type with depth. In Korea, since the introduction in the mid 1990's, the CPTu has been widely performed as the representative site investigation method. However, the correlations between the CPTu data and the V_S are also deficient in Korea. The CPTu is performed according to ASTM D 5778[(5)] and consists of pushing a cylindrical steel probe in the ground at a constant rate of 20 mm/sec and measuring the resistances to penetration. The conventional piezocone has a conical tip with 60° angle apex, 35.7 mm diameter body (10 cm^2 projected area), 150 cm^2 friction sleeve and transducer to measure porewater pressures at the shoulder behind the cone tip. As noted above, the standard CPTu provides corrected tip resistance (q_t) determined based on measured tip resistance (q_c) and net area ratio (a), sleeve friction (f_s) and excess porewater pressure (u) during the sounding in real time. Data are typically recorded every 2 to 5 cm of vertical penetration.

2.2 Geophysical In-situ Tests

There are several kinds of geophysical in-situ tests that can be used for stratigraphic profiling and delineation of subsurface geometries. These include the seismic techniques as well as the electromagnetic techniques. The seismic tests for obtaining mechanical waves are additionally useful for the determination of elastic properties of subsurface media, primarily the small-strain shear modulus (G) based on the shear wave velocity (V_S) and total mass density (ρ) in the geotechnical engineering perspective. Although various laboratory tests can be conducted to evaluate the V_S with reconstituted or undisturbed soil specimens, the measurement of V_S in soils can be efficiently accomplished using both the borehole and noninvasive seismic tests in field. Generally, to deduce the V_S profile at a site, the borehole seismic tests are more reliable than the noninvasive seismic tests.[6] The representative borehole seismic methods to determine the V_S profile for geotechnical design include the crosshole, downhole, uphole and inhole test and also the suspended sonic logging in the drilled boreholes. Additionally, the seismic CPTu (SCPTu) and seismic DMT (SDMT) as hybrid site investigation method applying the downhole seismic method into the conventional CPTu and DMT are currently used for evaluating the V_S profiles. In this study, to determine the V_S profiles, the crosshole, downhole and uphole seismic tests are conducted at the SPT sites, and the SCPTu are performed at the other sites. Therefore, these conducted borehole seismic tests are only discussed in this section.

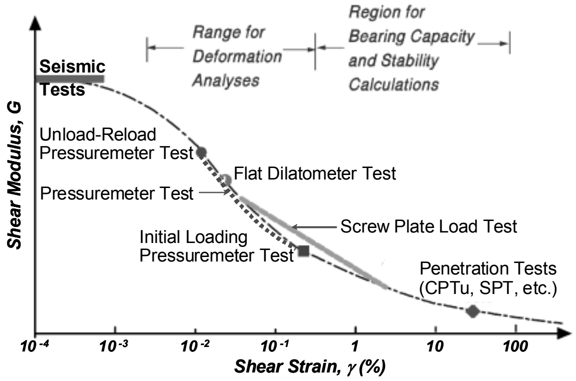
The crosshole seismic test is well suited for determining the V_S with depth and uses at least two boreholes, which consist of a hole for impulse energy source and the other holes for receivers. In order to have quantitative and quality assured results, the crosshole tests should be conducted in accordance with procedures established by ASTM D4428 M-91.[7] By fixing both the source and the receiver at the same depth in each borehole, the shear wave propagation time between boreholes at that depth is measured, and the V_S is calculated based on the propagation distance and time.

The downhole seismic test commonly used in geotechnical practices is appropriate to determine the V_S with depth and uses only single borehole for one or more geophone receivers. In the downhole test, an impulse source plank is located on the surface adjacent to the borehole. The shear wave propagation time from the plank to the receiver is measured, and the V_S is computed from both the distance of refracted propagation path based on Snell's law and the propagated travel time.[1),(8] A wooden plank is used for generating polarized shear waves (SH-wave).

The uphole seismic test can be performed in a single borehole and is similar to the downhole test in the geometrical wave propagation path. But the propagated directions between the uphole and downhole test are directly opposite. In the uphole test, a movable energy source is located in the borehole with receivers on the ground surface. The shear waves (SV-wave) in the borehole can be generated by the penetrating energy adopting the SPT[9),(10], which is utilized as the source in this study.

The seismic piezocone penetration test (SCPTu) was described in detail by Robertson et al.[11] and is recently performed to maximize the amount and types of subsurface data collected during site investigation. As the seismic cone is an ordinary CPTu probe with a built-in geophone (often measuring a couple of three components), the seismic wavelet signals can be obtained by means of the downhole test during the performing conventional CPTu. Thus, with the SCPTu, a single sounding produces four separate data with depth such as q_t, f_s, u and V_S, in which the former three data (q_t, f_s and u) and the latter V_S indicate the soil characteristics at large strains and small strains (< 10^{-3}%), respectively.

Seismic tests including downhole test measure the small strain response of a relatively large volume of ground, on the other hand, the penetration of the piezocone locally measures the large strain response of the ground since the average stress levels around the cone approximately equal failure of the soil. Figure 1



〈Figure 1〉 Shear Modulus with Strain and In-situ Testing Techniques[12] illustrates the order of strains corresponding to various measurements and the nonlinear strain dependency of soil deformation represented as shear modulus (G).[12] The shear modulus at small strain (G_{max} or G_0) can be realized as

$$G_{\max} = G_0 = \rho V_S^2 \tag{1}$$

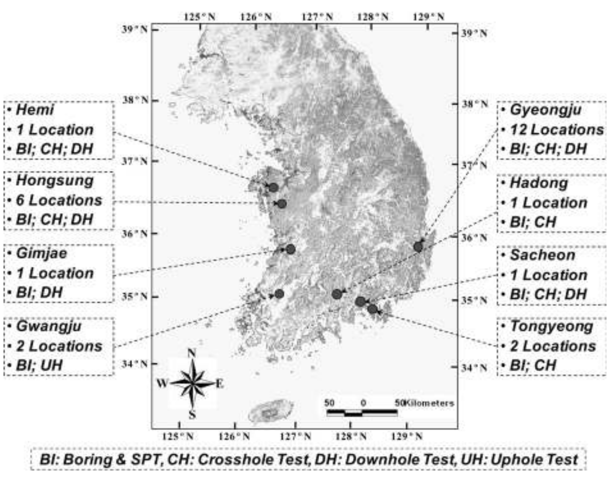
3. Correlation between Shear Wave Velocity and *N* Value

For the site characterization, the borehole drilling investigations with the SPT were performed at total 26 locations in 8 areas as shown in Figure 2. At each location, in-situ borehole seismic tests such as crosshole, downhole and uphole test were also conducted to determine the V_S with depth.

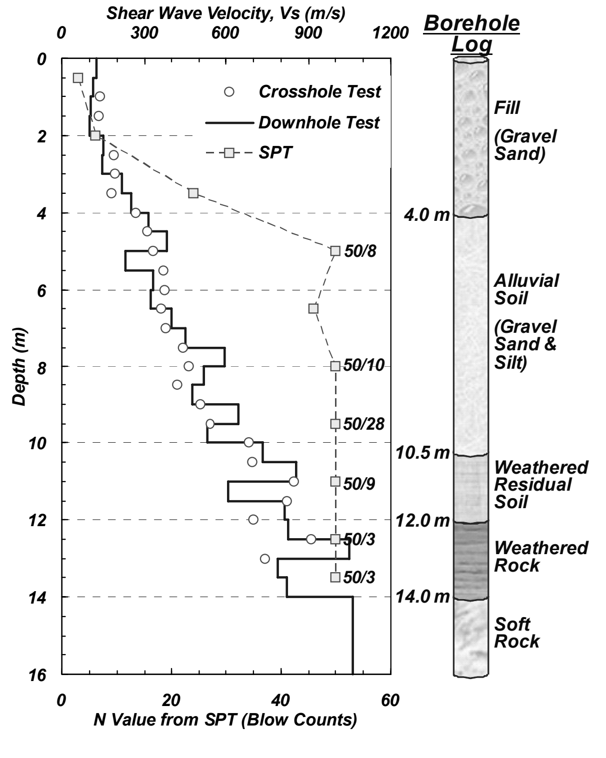
The SPTs penetrated into the ground with fill, alluvial soil (AS), weathered residual soil (WS) and weathered rock (WR) even though the exploratory boreholes were reached to soft or hard rock and the V_S profiles were evaluated from surface soil to engineering bedrock.[6] Figure 3 shows an example of testing results at a site in Gyeongju. The V_S determined from borehole seismic tests and N value obtained from SPT with depth are presented together with the borehole log. In this case of the application of two seismic testing methods, two V_S values from crosshole test and downhole test match with one N value, and all two V_S values were used to deduce the correlation between the V_S and N value with each seismic test method and for all methods.

In order to determine empirically the V_S from the N value of SPT in Korea, correlations between the V_S and N value have been suggested merely for local areas in several studies.[13],[14] On the other hand, this paper proposes the correlations between the V_S and N value across Korea based on the testing results in soils and weathered rock at 8 areas including the prior study areas.[13],[14]

The number of data pairs is 377 sets for all soils from three borehole seismic tests: crosshole, downhole and uphole tests. In the case of blow counts larger than 50 (e.g., 50/28 or 50/3) among measured N value data, the N values were extrapolated linearly into corresponding 30 cm penetration to analyze the regression between the V_S and N value. The extrapolation method for determining the N value in stiff soils needs to be studied by acquiring the SPT blow counts for the full penetration of 30 cm in weathered or stiff soils and weathered rocks in Korea[15] although the linear extrapolation method was adopted for this study. The SPT is affected by several factors, for instances overburden stress, rod length, equipment type, and so on, thus the N value measured in

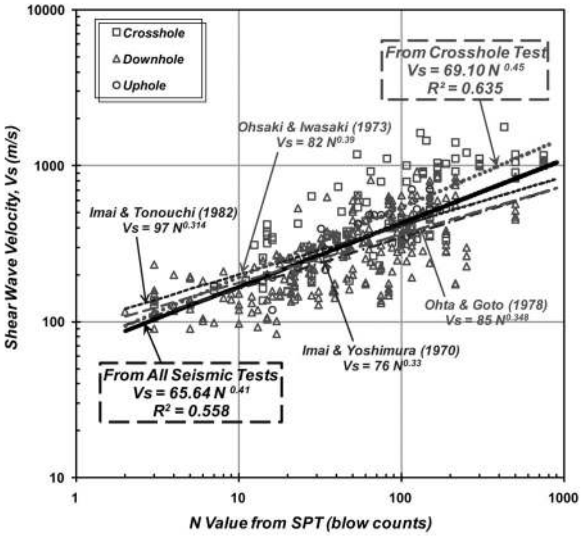


〈Figure 2〉 Information of the Borehole Drilling Sites in Korea



〈Figure 3〉 Typical Test Result from the Borehole Drilling Sites field should be corrected into N_{60} or $(N_1)_{60}$. Nevertheless, the measured N values have been directly utilized in a number of geotechnical engineering practices. Considering these practical circumstances, in this study, the N-V_S correlations were derived first using the measured N values without any corrections.

The resulted N-V_S correlations were presented as a form of power function in Table 1 and Figure 4. In Table 1, the N-V_S correlations grouped based on geologic conditions were also listed together with the coefficient of determination (R^2). The N-V_S correlations with soil types may be less useful than that for all soil, because of the restriction of the number of data with soil types and the corresponding low R^2 values. In addition, the $(N_1)_{60}$-V_S correlation based only on the crosshole test is presented in Figure 4, because the crosshole test is known as the most reliable seismic testing method.(6) As shown in Figure 4, the proposed correlation for all soils in this study is in good agreement with other correlations(16-19), which were deduced in foreign countries. Whereas, the correlation only using the crosshole test results has differently larger exponent and correspondently steep slope comparing with other correlations, despite the higher R^2 value. Particularly, the proposed N-V_S correlations for all soils based on all seismic tests and crosshole test are expected to be utilized for the preliminary determination only of V_S using N value for geotechnical earthquake engineering practices in Korea although the correlation do not reflect all of the characteristic deformation behaviors of soils due to the differences between the borehole seismic tests and the geotechnical penetration tests including the SPT.

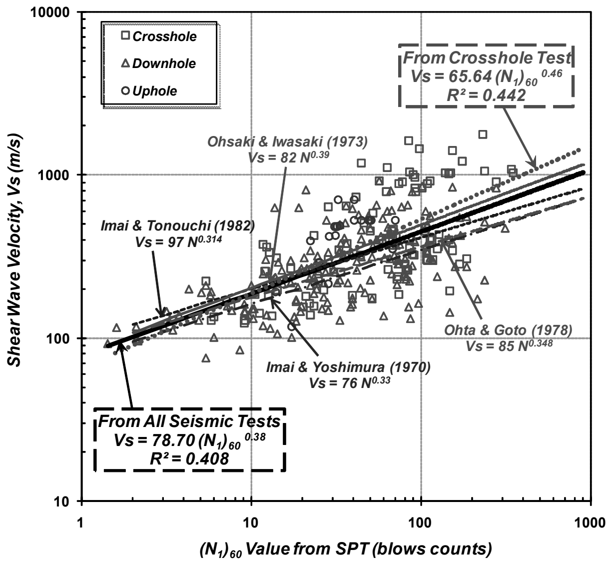


〈Figure 4〉 Correlation between V_S and Measured N Value for All Soils in Korea

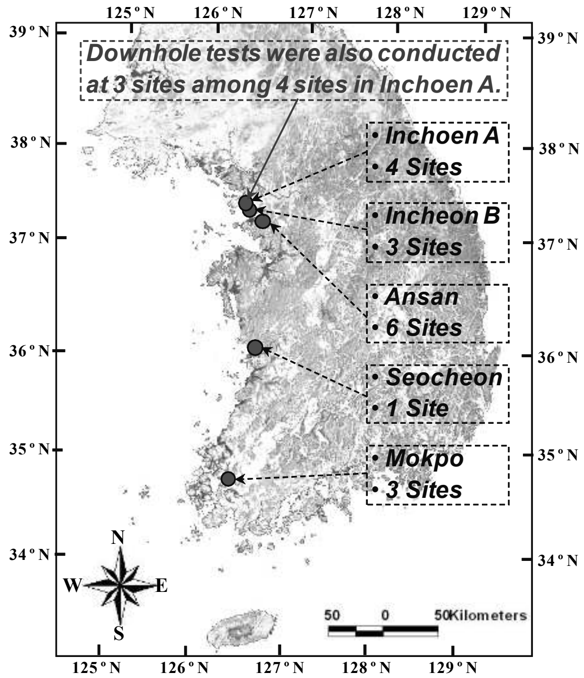
The N value measured during the SPT in field must be corrected considering the field-testing circumstances, and then the corrected N value can be used for evaluating soil characteristics.(20),(21) Thus, in this study, on the basis of the correction factors(21),(22), the measured N values were corrected into the $(N_1)_{60}$ with the consideration of both the field procedures to the standard energy ratio of 60 % and the overburden stress. The correlation between the V_S and $(N_1)_{60}$ for all soils based on all three seismic testing methods in Korea is shown in Figure 5, together with that based only on the crosshole test. The R^2 value in the case of $(N_1)_{60}$ for all soils is lower than that of measured N value, and the R^2 value from all seismic tests is somewhat lower than that only from the crosshole test. Although the correlationship on the $(N_1)_{60}$ is lower than that on the measured N and the correlations in this paper require further modification by accumulating more field testing data, the $(N_1)_{60}$-V_S correlations for all soils from all seismic test results and crosshole test results would be useful in the preliminary estimation of V_S using N value particularly in Korea.

〈Table 1〉 Correlations between Shear Wave Velocity and Measured N Value in Korea

Geology	Soil type	Correlations	R^2
Alluvial soil (AS)	Gravel	V_S = 78.63 $N^{0.361}$	0.331
	Sand and silt	V_S = 82.01 $N^{0.319}$	0.339
Weathered residual soil (WS)	Sand	V_S = 75.76 $N^{0.371}$	0.282
Weathered rock (WR)	Sand	V_S = 107.94 $N^{0.418}$	0.220
All soils		V_S = 65.64 $N^{0.407}$	0.558



〈Figure 5〉 Correlation between V_S and Corrected N Value, $(N_1)_{60}$, for All Soils in Korea



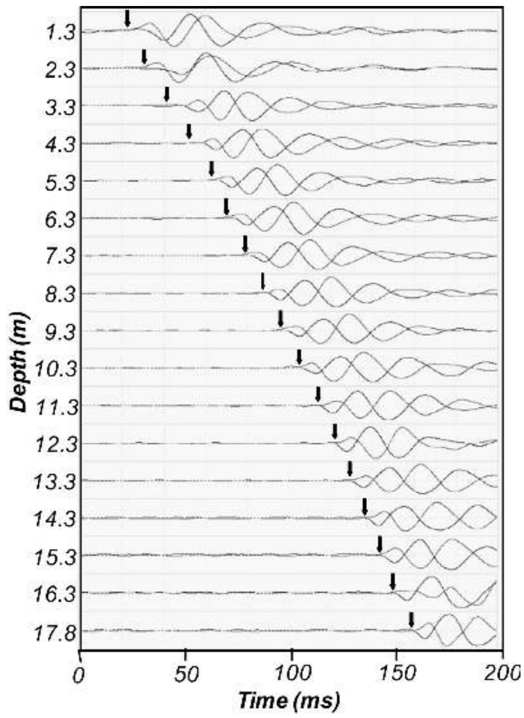
〈Figure 6〉 Information of the Seismic Piezocone Penetration Testing Sites in Korea

4. Correlation between Shear Wave Velocity and Piezocone Penetrating Data

As part of a synthetic characterization of soil deposits in Korea, the seismic piezocone penetration tests (SCPTu) were performed at total 17 sites in 5 areas. The testing sites which are mainly composed of marine and alluvial fine soils are located at the western coastal regions in Korea, as shown in Figure 6. From the SCPTu, both the penetrating data such as q_t, f_s and u, and the V_S data were determined. Among the sites of interesting for this study, 4 sites in Incheon A area were part of the target sites for analyzing the statistical correlations between the V_S and CPTu data as the beginning in Korea by Kim et al..[23] In this study, in order to improve the empirical correlations for determining the V_S using the peizocone penetrating data, the SCPTu was additionally performed particularly at the western coastal sites in Korea and the data obtained from the additional SCPTu's were analyzed by combining the prior data by Kim et al..[23]

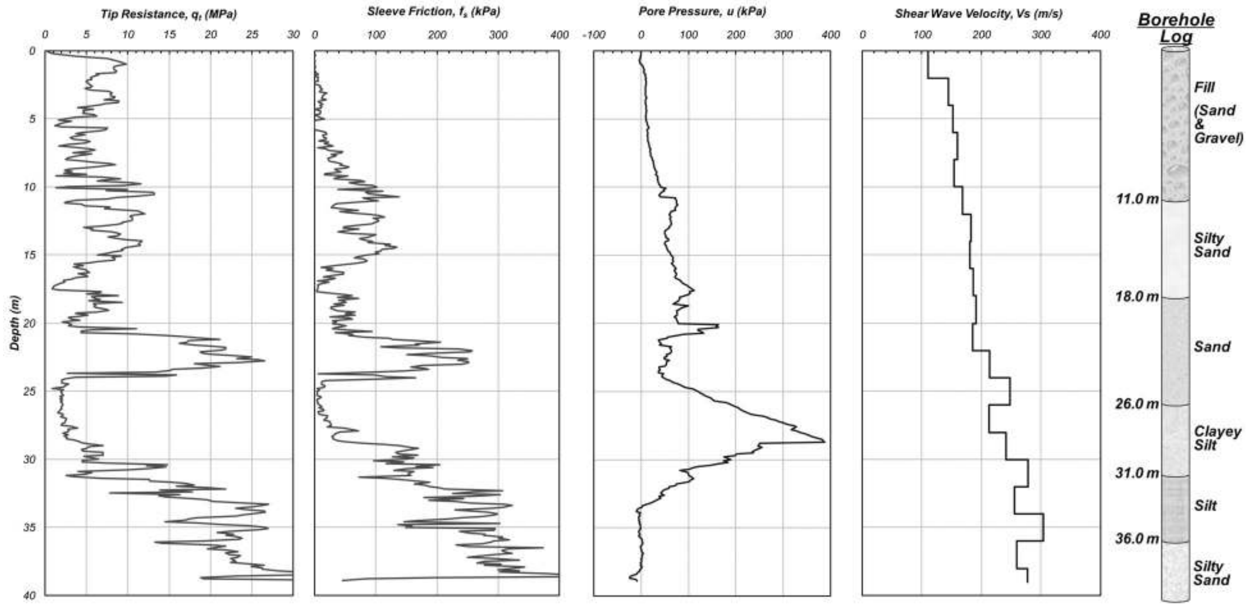
4.1 Results from Seismic Piezocone Penetration Test

Horizontal polarized shear wave velocities were measured at depth intervals of 1 to 4 m by SCPTu. Figure 7 shows typical wavelets with depth obtained from the downhole test of SCPTu at a site in Seocheon



〈Figure 7〉 Representative Wavelets with Depth from the SCPTu

area. In Figure 7, the markers indicate the first arrivals of shear waves. From the first arrivals with depth in the wavelets, the V_S profiles were determined using the refracted ray path method based on Snell's law.[8],[24] Both the V_S profile and the penetration data of q_t, f_s and u were acquired from the SCPTu at all testing sites, and



〈Figure 8〉 Representative Results (q_t, f_s, u and V_S) of the SCPTu

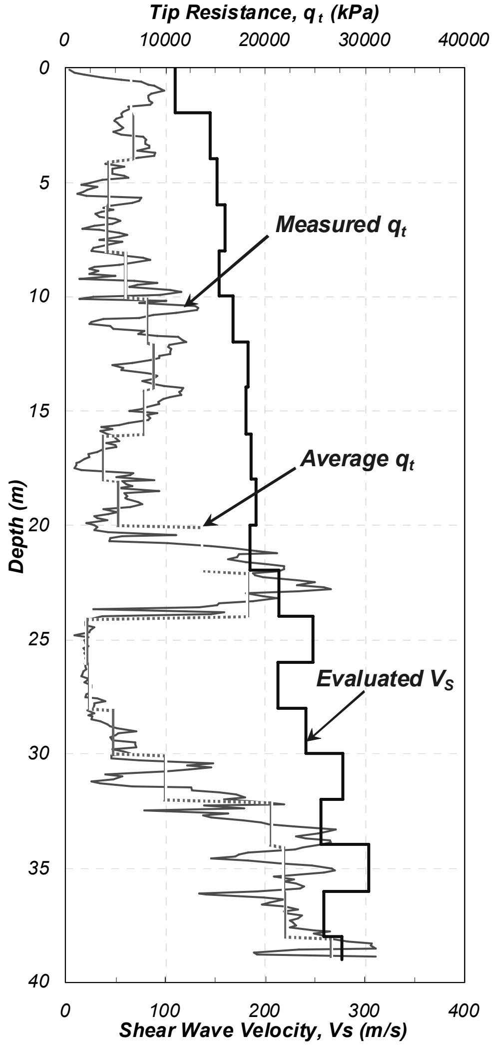
representatively the q_t and V_S at a site in Incheon A area were presented in Figure 8. It shows the similar trend with depth between the V_S profile and the q_t value, like other SCPTu results in this study.

To match the continuous penetration data with the stepped V_S value for analyzing their correlations, the average of CPTu data (q_t, f_s and u) were calculated considering the depth intervals for the downhole test of SCPTu. Figure 9 shows an example plot of the revaluated q_t values with depth and V_S profile. From the existing correlation researches[(23),(25-27)], it has been known that the V_S was related to not only the CPTu data but other geotechnical parameters such as overburden effective stress (σ'_{v0}), void ratio (e_0), overconsolidation ratio (OCR), plasticity index (PI), and so on. In this study, the σ'_{v0} among them was considered as a correlated parameter for V_S value, by means of multiple statistical regression modeling. For the regression analyses, pore pressure ratio (B_q) which is converted from measured excess pore pressure (u) from the CPTu was employed as defined by

$$B_q = (u - u_0)/(q_t - \sigma_{vo}) \quad (2)$$

where u_0 is hydrostatic pressure.

Since soil samples cannot be obtained in CPTu, soil classification charts are usually employed to identify soil



〈Figure 9〉 Determination of Average CPTu Data (case of q_t) with Depth for Matching V_S Interval type from CPTu data. An index for soil type classification (I_C) proposed by Jefferies and Davis[28] is expressed as

$$I_C = \sqrt{[3-\log\{Q_t(1-B_q)\}]^2 + [1.5+1.3\{\log F_r\}]^2} \quad (3)$$

where $Q_t = \{q_t - \sigma_{vo}\}/\sigma'_{vo}$ and σ_{v0} is overburden total stress. According to the I_C value, soil types were classified into clay for I_c >2.54 and sand for I_c <2.54. The number of data set for the correlations between V_S and CPTu data is 162 sets for clay, 126 sets for sand and total 288 sets for both soils.

4.2 Correlations between V_S and CPTu Data

Based on the literature reviews[23,25-27], the multiple statistical regression analyses for the correlation between CPTu data (q_t, f_s, u and σ'_{v0}) and V_S were executed with various forms of power functions listed in Table 2. In particular, q_t was regarded as a main parameter for the statistical regression analyses in most cases, with the exception of a case of f_s as the main parameter, which is correspondent with a correlation form suggested by Hegazy and Mayne.[25]

The usefulness of correlations was examined in terms of R^2, which generally increases as the increase of the number of individual parameters for regression. Thus, Cor11 in Table 2 could be utilized for estimating empirically the V_S values based on the CPTu data, and also Cor03, Cor07 and Cor09 in Table 2 could be useful, in which R^2 values show more than 0.75 for all soils and furthermore over 0.83 for clay (see Table 2) despite the R^2 values ranging from 0.65 to 0.69 for sand. Particularly, the fact that the proposed four correlations contain a specific parameter, σ'_{v0}, indicates significance of σ'_{v0} on the correlation between CPTu penetration data and V_S value. As the results of multiple statistical regression analyses for deducing the correlations between the V_S and CPTu data, the coefficients and exponents of the Cor03, Cor07, Cor09 and Cor11 (see Table 2) for all soils, clay and sand are illustrated in Table 3. Furthermore, the four correlations could be applicable to the preliminary evaluation of V_S profile for earthquake engineering practices using conventional CPTu data at soil deposits in Korea, in spite of the different strain levels between testing methods for the V_S and static soil properties. Nevertheless, for reliably evaluating the V_S profile at a site, a series of seismic tests should be preferentially considered and these correlations should be used restrictively for the purpose of preliminary estimation of the V_S at the site performing only the CPTu in Korea on the basis of the prudent judgment by geotechnical expert. The authors suggest that the CPTu data-V_S correlations be considered as providing a general framework for the western costal region in Korea in view of the limitation of this study, such as relatively small number of SCPTu data and restricted site conditions. Moreover, the corre-

〈Table 2〉 Equation Forms for Correlation between Shear Wave Velocity and Piezocone Penetrating Data

Symbol	Correlation form*	R^2		
		All soils	Clay	Sand
Cor01	$V_S = \alpha(q_t)^{k1}$	0.617	0.741	0.527
Cor02	$V_S = \alpha(q_t)^{k1}(f_s)^{k2}$	0.633	0.743	0.621
Cor03	$V_S = \alpha(q_t)^{k1}(\sigma'_{v0})^{k2}$	0.756	0.832	0.650
Cor04	$V_S = \beta(f_t) + \gamma$	0.531	0.359	0.554
Cor05	$V_S = \alpha(q_t)^{k1}(1+B_q)^{k2}$	0.621	0.744	0.545
Cor06	$V_S = (\alpha\log(q_t) - \delta)^{k1}(100 f_s / q_t)^{k2}$	0.634	0.751	0.611
Cor07	$V_S = \alpha(q_t)^{k1}(f_s)^{k2}(\sigma'_{v0})^{k3}$	0.759	0.836	0.690
Cor08	$V_S = \alpha(q_t)^{k1}(f_s)^{k2}(1+B_q)^{k3}$	0.633	0.745	0.629
Cor09	$V_S = \alpha(q_t)^{k1}(\sigma'_{v0})^{k2}(1+B_q)^{k3}$	0.758	0.838	0.651
Cor10	$V_S = \alpha(q_t)^{k1}(\sigma'_{v0}/f_s)^{k2}(1+B_q)^{k3}$	0.651	0.765	0.545
Cor11	$V_S = \alpha(q_t)^{k1}(f_s)^{k2}(\sigma'_{v0})^{k3}(1+B_q)^{k4}$	0.762	0.840	0.691

*The units are m/s for V_S and kPa for q_t, f_s and σ'_{v0}.

〈Table 3〉 Coefficients and Exponents for the Proposed CPTu Data-V_S Correlations in Korea

Symbol	Sort	All soils	Clay	Sand
Cor03	α	17.181	13.953	17.063
	k1	0.148	0.188	0.158
	k2	0.229	0.215	0.213
	R^2	0.756	0.832	0.650
Cor07	α	20.495	12.468	33.375
	k1	0.119	0.202	0.047
	k2	0.028	-0.027	0.132
	k3	0.223	0.229	0.161
	R^2	0.759	0.836	0.690
Cor09	α	18.602	16.332	16.083
	k1	0.135	0.152	0.167
	k2	0.237	0.241	0.207
	k3	-0.130	-0.152	0.333
	R^2	0.758	0.838	0.651
Cor11	α	24.215	14.716	32.159
	k1	0.091	0.168	0.053
	k2	0.037	-0.018	0.131
	k3	0.232	0.246	0.158
	k4	-0.181	-0.126	0.169
	R^2	0.762	0.840	0.691

lations between the V_S and piezocone penetrating data in Korea require the quantitative comparisons with those for other countries by accumulating more the SCPTu data and corresponding further modification of the correlations.

5. Conclusions

To propose improved empirical equations for determining the V_S profiles based on both N values and CPTu penetrating data in Korea, the SPT were conducted together with the borehole seismic tests and the SCPTu were performed at various sites. From the testing results, both the N-V_S and the CPTu data-V_S correlations were proposed for soil layers underlying bedrock in Korea.

Based on the borehole seismic testing results in Korea, the N-V_S correlations were deduced based on the measured N values for not only soil types but also all soils, considering engineering practical circumstances. In particular, the deduced N-V_S correlation for all soils in Korea was in good agreement with prior other proposed correlations for foreign sites and would be applied to the determination of V_S using N value. From the multiple statistical regression modeling based on the SCPTu results, the CPTu data-V_S correlations were investigated with the form of power functions. The representative correlations containing a specific parameter, σ'_{v0}, were proposed and confirmed that they could be useful in the preliminary estimation of V_S for geotechnical engineering practices in Korea.

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References

1. Sun, C. G., *Geotechnical Information System and Site Amplification Characteristics for Earthquake Ground Motions at Inland of the Korean Peninsula*, Ph.D Dissertation, Seoul National University, 2004.
2. Sun, C. G., Chung, C. K., Shin, J. S., and Chi, H. C., "Empirical Correlations between Geotechnical In-situ Parameters and Shear Wave Velocity from Borehole Seismic Tests," *Proceedings of the 10th International Symposium on Recent Advances in Exploration Geophysics*, March 30-31, Daejeon, Korea, 2006, pp. 151-158.
3. Mayne, P. W., Christopher, B. R., and DeJong, J., *Manual on Subsurface Investigations: Geotechnical Site Characterization*, National Highway Institute Publication No. FHWA NHI-01-031, Federal Highway Administration, Wahsington, D.C., 2001.
4. ASTM, "Standard Test Method for Penetration Test and Split-barrel Sampling of Soils (D 1586 - 99)," *2002 Annual Book of ASTM Standards*, Sect. 4, Vol. 04.08, American Society for Testing and Materials, Philadelphia, 2002.
5. ASTM, "Standard Test Method for Performing Electronic Friction Cone and Piezocone Penetration Testing of Soils (D 5778-95)," *2000 Annual Book of ASTM Standards*, Sect. 4, Vol. 04.09, American Society of Testing and Materials, Philadelphia, 2000.
6. Sun, C. G., Kim, D. S., and Chung, C. K., "Geologic Site Conditions and Site Coefficients for Estimating Earthquake Ground Motions in the Inland Areas of Korea," *Engineering Geology*, Vol. 81, No. 4, 2005, pp. 446-469.
7. ASTM, "Standard Test Method for Crosshole Seismic Testing (D 4428 / D 4428 M-91)," *1996 Annual Book of ASTM*

Standards, Sect. 4, Vol. 04.08, American Society of Testing and Materials, Philadelphia, 1996.

8. Kim, D. S., Bang, E. S., and Kim, W. C., “Evaluation of Various Downhole Data Reduction Methods for Obtaining Reliable Vs Profiles,” *Geotechnical Testing Journal*, Vol. 27, No. 6, 2004, pp. 334-341.
9. Tanimoto, K., Takahashi, Y., Murata, Y., Yamamoto, M., and Sugawara, N., “Examination of Liquefaction Potential by Seismic Tomography after the Hyogoken-Nambu Earthquake in the Reclaimed Land of Kobe,” *Proceedings of the 1st International Conference on Site Characterization - ISC’98*, Atlanta, 1998, pp. 531-536.
10. Kim, D. S., Bang, E. S., and Seo, W. S., “Evaluation of Shear Wave Velocity Profiles by Performing Uphole Test Using SPT,” *Journal of the Korean Geotechnical Society*, Vol. 19, No. 2, 2003, pp. 135-146 (in Korean).
11. Robertson, P. K., Campanella, R. G., Gillespie, D., and Rice, A., “Seismic CPT to Measure In-situ Shear Wave Velocity,” *Journal of Geotechnical Engineering*, ASCE, Vol. 112, No. 8, 1986, pp. 791-803.
12. Mayne, P. W. and Schneider, J. A., “Evaluating Drilled Shaft Response by Seismic Cone,” *Foundations and Ground Improvement*, Geotechnical Special Publication No. 113, ASCE, 2001, pp. 655-669.
13. Sun, C. G., Chung, C. K., and Kim, D. S., “A Proposition of Site Coefficients and Site Classification System for Design Ground Motions at Inland of the Korean Peninsula,” *Journal of the Korean Geotechnical Society*, Vol. 21, No. 6, 2005, pp. 101-115 (in Korean).
14. Sun, C. G., Kim, B. H., and Chung, C. K., “Investigation on Weathering Degree and Shear Wave Velocity of Decomposed Granite Layer in Hongsung,” *The KSCE Journal of Civil Engineering*, Vol. 26, No. 6C, 2006, pp. 431-443 (in Korean).
15. Sun, C. G., Han, J. T., Choi, J. I., Kim, K. S., and Kim, M. M., “Investigation into the Input Earthquake Motions and Properties for Round Robin Test on Ground Response analysis,” *Proceedings of the Korean Geotechnical Society Autumn National Conference 2007*, Busan, 2007, pp. 266-292 (in Korean).
16. Imai, T. and Yoshimura, Y., “Elastic Wave Velocity and Soil Properties in Soft Soil,” *Tsuchi-to-Kiso*, Vol. 18, No. 1, 1970, pp. 17-22 (in Japanese).
17. Ohsaki, Y., and Iwasaki, R., “On Dynamic Shear Moduli and Poisson’s Ratio of Soil Deposits,” *Soils and Foundations*, Vol. 13, No. 4, 1973, pp. 61-73.
18. Ohta, Y. and Goto, N., “Empirical Shear Wave Velocity Equations in terms of Characteristic Soil Indexes,” *Earthquake Engineering and Structural Dynamics*, Vol. 6, No. 2, 1978, pp. 167-187.
19. Imai, T. and Tonouchi, K., “Correlation of N-value with S-wave Velocity and Shear Modulus,” *Proceedings of the 2nd European Symposium on Penetration Testing*, Amsterdam, 1982, pp. 57-72.
20. Aggour, M. S. and Radding, W. R., *Standard Penetration Test (SPT) Correction*, Report No. MD02-007B48, Maryland State Highway Administration, Baltimore, 2001.
21. Oh, S. and Sun, C. G., “Combined Analysis of Electrical Resistivity and Geotechnical SPT Blow Counts for the Safety Assessment of Fill Dam,” *Environmental Geology*, Vol. 54, No. 1, 2008, pp. 31-42.
22. Skempton, A. W., “Standard Penetration Test Procedures and the Effects in Sands of Overburden Pressure, Relative Density, Particle Size, Gaining, and Overconsolidation,” *Geotechnique*, Vol. 36, No. 3, 1986, pp. 425-447.
23. Kim, H. J., Cho, S. M., and Sun, C. G., “Statistical Correlations between Shear Wave Velocity and Penetrating Characteristics Using the Seismic Piezo-cone Penetration Tests (SCPTU),” *The KSCE Journal of Civil Engineering*, Vol. 25, No. 3C, 2005, pp. 215-226 (in Korean).
24. Kim, H. J., Sun, C. G., Cho, S. M., and Heo, Y., “Determination of Shear Wave Velocity Profiles from the SCPT,” *The KSCE Journal of Civil Engineering*, Vol. 25, No. 3C, 2005, pp. 201-214 (in Korean).
25. Hegazy, Y. A. and Mayne, P. W., “Statistical Correlations between Vs and Cone Penetration Data for Different Soil Types,” *Proceedings of the International Symposium on Cone Penetration Testing- CPT’95*, Vol. 2, Linkoping, 1995, pp. 173-178.
26. Mayne, P. W. and Rix, G. J., “Correlation between Shear Wave Velocity and Cone Tip Resistance in Natural Clays,” *Soils and Foundations*, Vol. 35, No. 2, 1995, pp. 107-110.
27. Madiai, C. and Simoni, G., “Shear Wave Velocity-penetration Resistance Correlation for Holocene and Pleistocene Soils of an Area in Central Italy,” *Proceedings of the ICS-2 on Geotechnical and Geophysical Site Characterization*, Porto, 2004, pp. 1687-1694.
28. Jefferies, M. G. and Davis, M. P., “Use of the CPTu to Estimate Equivalent SPT N_{60},” *ASTM Geotechnical Testing Journal*, Vol. 16, No. 4, 1993, pp. 458-468.