

Article

Empirical Correlation between Standard Penetration Resistance (SPT-N) and Shear Wave Velocity (V_s) for Soils in Metro Manila, Philippines

Arturo S. Daag , Oliver Paul C. Halasan, Arielle Anne T. Magnaye, Rhommel N. Grutas and Renato U. Solidum, Jr.

Department of Science and Technology—Philippine Institute of Volcanology and Seismology, C.P. Garcia Ave., Diliman, Quezon City 1101, Philippines

* Correspondence: arturo.daag@phivolcs.dost.gov.ph

Abstract: The measurement of the shear wave velocities (V_s) of soils is an important aspect of geotechnical and earthquake engineering, due to its direct relation to the shear modulus (G), which in turn influences the stress–strain behavior of geomaterials. V_s can be directly measured or estimated using a variety of onsite tests or in a laboratory. Methods such as downhole PS logging require boreholes and may not be logistically and economically feasible in all situations. Many researchers have estimated V_s from other geotechnical parameters, such as standard penetration test resistance (SPT-N), by means of empirical correlations. This paper aimed to contribute to this subject by developing an empirical relationship between V_s and SPT-N. Data from twenty sites in Metro Manila were obtained from geotechnical investigation reports. V_s profiles of the same sites were also acquired using the refraction microtremor method. New empirical relationships were developed for all, sandy, and clayey soil types, using a non-linear regression method that is applicable for Metro Manila soils. Statistical evaluation and comparison of the proposed correlations with other previous works suggested the viability of the empirical model.

Keywords: shear wave velocity; standard penetration test; refraction microtremor; empirical correlation; Metro Manila



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1. Introduction

The measurement of the shear wave velocities (V_s) of soils is an important aspect in the application of geotechnical and earthquake engineering. This geophysical parameter is related to the shear modulus (G) through the elastic theory, in the equation $G = \rho V_s^2$, where ρ is the density of material. The stress–strain behavior of materials is then dictated by the shear modulus, as the strain is directly affected by this parameter [1]. This relationship is also important in ground response analysis, as it is used to evaluate the dynamic response of soils during earthquakes. The seismic shear wave velocity of the upper 30-m soil layer (V_{s30}) largely influences the ground motion amplification and is therefore considered an important parameter in earthquake engineering [2]. Additionally, the shear wave velocity of geomaterials is also used in studies on soil stratigraphy, liquefaction analysis, and site-specific subsurface modeling [3–5].

Shear wave velocities can be measured or estimated using a variety of laboratory or field tests. Bender element and resonant columns are some of the laboratory techniques that measure V_s . The accuracy of these techniques is greatly dependent on the degree of disturbance of the soil samples [6]. In situ field measurements include invasive methods such as down-hole, cross-hole, and up-hole tests. These techniques require the drilling of boreholes to a particular depth and, thus, may not be economically feasible in all situations. On the other hand, non-invasive geophysical methods, such as spectral analysis of surface waves (SASW), multichannel analysis of surface waves (MASW), refraction microtremor

(ReMi), among others, can also estimate V_s on site. These techniques do not require drilling equipment and only use acoustic sensors to determine the subsurface shear wave velocities.

There have been attempts to correlate this geophysical parameter to other physically measured soil properties. These empirical correlations between the geotechnical parameters of soil and V_s were established in order to aid in soil behavior estimation and seismic demand analysis (e.g., Azam Ghazi et al., 2015 [7]; Gautam, 2017 [2]). However, these relationships are only accepted in localized data. In Japan, many works regarding this area were done in the 1970s, utilizing datasets from different regions (i.e., Imai and Yoshimura, 1970 [8]; Ohba and Toriumi, 1970 [9]; Shibata, 1970 [10]; Ohta et al., 1972 [11]; Fujiwara, 1972 [12]; Ohsaki and Iwasaki, 1973 [13]; Imai, 1977 [14]). These works mainly evaluated the dynamic response of soils (e.g., liquefaction) due to earthquakes. This continued into the 1980s, as Imai and Tonouchi (1982) [15] proposed a correlation with the most data points ($n = 1654$) based on the relative density of the subsurface soil (N-value), soil type, and geologic age. The work of Imai and Tonouchi (1982) also indicated that clayey layers have higher V_s values in comparison to sandy soils. In the United States, a similar correlation was proposed by Seed and Idriss (1981) [16], to determine liquefaction susceptibility of alluvium and marine sands. Their correlation utilizes corrected SPT parameters such as the N_{60} and $(N_1)_{60}$. This proposal is similar with the works by Seed et al., (1985) [17]; Sykora and Stokoe (1983) [18], Rollins et al. (1998) [19], and Brandenburg et al., (2010) [20].

Other countries have developed similar empirical correlations. Over the past decades, works by Kalteziotis et al. (1992) [21], Pitilakis et al. (1999) [22], Athanasopoulos (1995) [23], Raptakis et al. (1995) [24], Tsiambaos and Sabatakakis (2011) [25] have been completed in Greece. From Turkey, works by Iyisan (1996) [26], Kayabali (1996) [27], Hasancebi and Ulusay (2007) [28], Koçkar and Akgün (2008) [29], Dikmen (2009) [30], and Akin et al. (2011) [31] also explored the empirical correlations between V_s and SPT-N values and other geotechnical parameters. A considerable number of works on this topic have also been done in India: Anbazhagan and Sitharam (2010) [32], Anbazhagan et al. (2013) [33], Hanumantharao and Ramana (2008) [34], and Uma Maheswari et al. (2010) [35]. Kuo et al. (2011) [36] correlated V_s in terms of soil characteristics such as depth, soil type, and SPT-N value, using datasets from Taiwan.

Due to differences in soil type and properties from region to region, which arise from differences in geologic settings and active geomorphic processes, the proposed empirical correlations are local and were only extrapolated to areas with a similar lithology. The application was generally constrained to similar soil conditions and geomorphic settings. As such, despite the numerous proposed empirical correlations, there is still a great importance in correlating V_s and geotechnical parameters using datasets from local settings. Additionally, a variety of reasons, such as lack of drilling and geophysical equipment, personnel, and/or budget, can hinder the carrying out of downhole measurements of V_s , especially in smaller projects in the Philippines. Direct V_s measurements may be preferable, but in most cases where this is not feasible, empirical correlations between V_s and geotechnical parameters can be useful for site investigations.

The main objective of this paper was to develop an empirical relationship between V_s values from a refraction microtremor to N-values from standard penetration test drillings, using statistical regression analysis. Twenty sites (20) in Metro Manila, Philippines were surveyed using the refraction microtremor technique to establish one-dimensional V_s profiles correlated to N-values from SPT. The proposed empirical relationship between V_s and the N-value of soils in Metro Manila represents an important development in site characterization techniques and seismic microzonation efforts in the study area.

2. The Study Area

Metropolitan Manila (Metro Manila) is the capital region of the Philippines (Figure 1), which is also the center of the economy and the most populated areas. The region is composed of several cities and municipalities, sprawled over an area of around 620 square kilometers. It lies in the southern extension of the Luzon Central Valley. In the early stages

of the development of the Central Valley, rapid sedimentation from highlands persisted until the Late Cretaceous, intercalated with tuff and other volcanic products [37]. During the Late Tertiary and Quaternary periods, complex tectonic events led to the basic geologic structure of Metro Manila at present. This geologic evolution has produced three distinct terranes in the metropolis: the Coastal Lowland, Central Plateau, and the Marikina Valley. East of the metropolis, the uplands of Rizal province with basement-ophiolite complexes can be found. To the west, this region is bounded by Manila Bay.

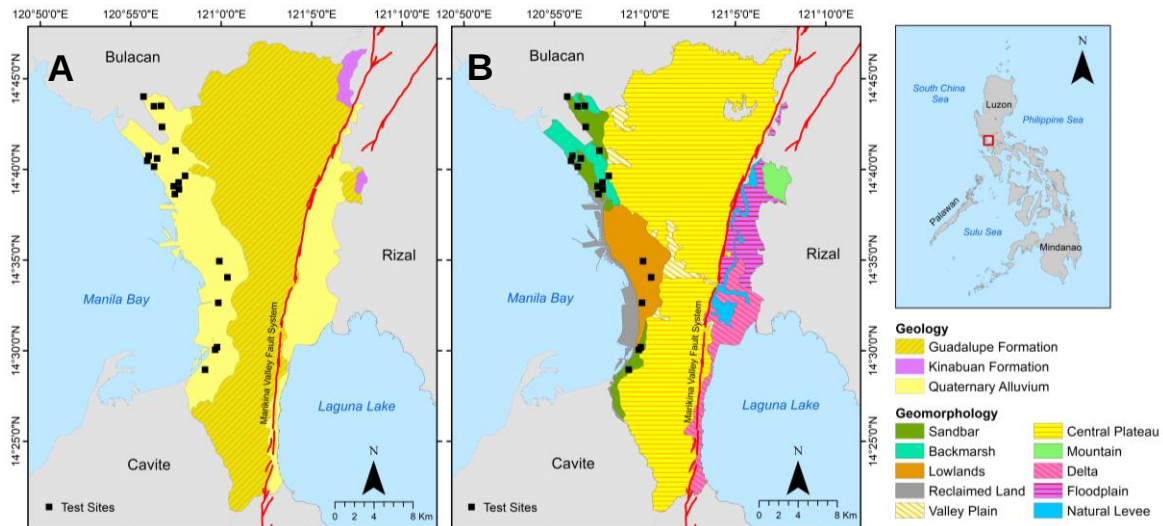


Figure 1. (A) Geological and (B) geomorphologic map of Metro Manila, Philippines, and the locations of the refraction microtremor surveys. Geologic map modified from BMG (1983) [38] and geomorphologic map obtained from MMIERS (2004) [39]. Locations of the testing sites are also depicted in black squares.

The Coastal Lowland is the flat and low plain section of Metro Manila, facing the Manila Bay. This section can be further subdivided into deposits from sand bars, backmarshes, tidal flats, the Pasig River delta, and some reclaimed land. This Quaternary Alluvium deposit has a thickness that can reach up to 40 m [40]. Sixty percent of the Metro Manila area is underlain by the Central Plateau, which is the geomorphic manifestation of the bedrock of the region, namely the Diliman Tuff member of the Pleistocene Guadalupe Formation. This lithologic member is made of flat-lying sequences of medium to thin-bedded, fine-grained vitric tuff and welded pyroclastic breccias. Minor fine to medium-grained tuffaceous sandstone was also reported to be part of this unit [41]. The Marikina Valley is the flat section on the eastern bounds of the metropolis, with lower elevations than the Central Plateau. This is produced by a pull-apart basin associated with the West Valley Fault (WVF) and East Valley Fault (EVF), collectively called the Marikina Valley Fault System [42]. Quaternary alluvium deposits in this section are associated with the floodplain of the Marikina River and the delta along the Laguna de Bay. Surface deposits on this sector are reported to reach up to 50 m in thickness [40].

Geologic field mapping and different subsurface investigations have revealed that most of the Metro Manila soils and sediments are composed of thick sequences of pyroclastic and epiclastic deposits. Pyroclastic deposits, primarily tuff materials, are derived from eruptions of nearby volcanoes in the region. The epiclastic deposits come from pyroclastic materials that were reworked by fluvial and lacustrine processes. Tan (1983) [43] reported that these epiclastic fluvial deposits are generally made of a sequence of loose to firm silty fine sand at the surface, underlain by very soft clayey silt or silty clay, further underlain by stiff to very stiff clay, and finally hard clay and silt, sometimes intercalated with very dense sand and/or gravel that grade into bedrock. The thickness and lateral continuity of these

layers is highly variable, such that during borehole investigations on a particular site, it is normal to encounter different thicknesses and sequences of soil and sediment deposits.

3. Field Investigations

3.1. Geotechnical Investigations

The most common type of geotechnical site investigation in the country is through the standard penetration test (SPT). The National Structural Code of the Philippines [44] requires at least one borehole for two-story structures and greater, with the number of boreholes determined depending on the footprint area of the building. This in situ geotechnical test involves the driving of a hollow tube into the soil, while noting the number of blows needed to push the tube sampler down a specific vertical distance. A 63.5 kg hammer is repeatedly dropped from a height of 76 cm to advance the tube, in three successive increments of 150 mm. The first 150 mm is considered as a seating penetration and is disregarded, while the total number of blows needed to penetrate the second and third 150-mm iterations is the determined N-value of that layer. This procedure is described in the ASTM D1586 [45] guideline. The number of blow counts or N-value can be affected by a variety of factors. The most important factors include the amount of energy delivered to the tube in each impact of the hammer, the type of hammer, diameter of the borehole, and the length of the rod.

Standard penetration test reports of twenty sites in Metro Manila (Figure 1) were obtained from the Department of Education, and Department of Public Works and Highways of the Philippines. These SPT investigations were typically carried out as a prerequisite before the construction of school buildings and other structures. The sites selected to be included in this study were identified as having sufficient space, where geophysical surveys can be conducted and geotechnical data are available. Moreover, the spatial distribution was intended so that there are representatives of the various major geomorphic units identified in the coastal portion of the area. These sites are located along the western coast of Metro Manila, atop the Coastal Lowlands, and are expected to have relatively thick soil deposits. Specifically, the sites were built on top of sandbars, backmarshes, and lowland deposits.

Most of the boreholes have depths that reach up to 15 m, the typical depth requirement for low-story buildings in the country. In some cases, the depth can reach up to 30 m, particularly for sites with thicker soil profiles. On the other hand, there are also SPT investigations where the penetration only reaches up to five to ten meters, for sites with a shallower bedrock depth. In such cases, a coring procedure is employed to penetrate the target depth. The obtained soil samples from the SPT investigation were subjected to typical laboratory tests, such as grain size analysis, moisture content determination, Atterberg Limit test, soil classification, and unconfined compression test. A summary of the measured N-values and soil types identified for each depth in the twenty sites is presented in Table 1.

Table 1. Summary of the SPT from the twenty sites, indicating the location, water table depth, and Unified Soil Classification System (USCS) soil types at varying depths. The USCS scheme is adapted as the standard practice for soil classification for engineering purposes [46]. SM—silty sand, GM—silty gravel, ML—silt, CL—low plasticity clay, MH—high plasticity silt, SC—clayey sand, SP—poorly-graded sand, GP—poorly-graded gravel, CH—high plasticity clay, SW—well-graded sand, and GC—clayey gravel.

Site No.	Name	City	Long. (°)	Lat. (°)	Water Table Depth (m)	Depth (m)	Soil Type (USCS)
1	Wawang Pulo Elementary School	Valenzuela	120.928018	14.733015	0.2	0–1	SM
						1–2	GM
						2–5	SM
						5–6	ML
						6–15	CL
2	Pio Valenzuela Elementary School	Valenzuela	120.946090	14.707048	0.3	0.5	GM
						0.5–4.5	SM
						4.5–10	CL
						10–11.5	ML
						11.5–13	SM
13–15	CL						
3	Tagalag Elementary School	Valenzuela	120.938120	14.724660	0.7	0–15	SM
4	Coloong Elementary School	Valenzuela	120.944549	14.725007	4.0	0–10.0	ML
						10–15	SM
5	San Roque Elementary School	Navotas	120.938040	14.669389	0.8	0–6	SM
						6–12	MH
						12–25	ML
6	Tangos National High School	Navotas	120.932246	14.674792	0.6	0–1	SM
						1–2	SC
						2–3	SM
						3–6	SP-SM
						6–7.5	SC
						7.5–10.5	MH
						10.5–12	ML
						12–13.5	SC
						13.5–22.5	MH
22.5–25	SM						
7	Kapitbahayan Elementary School	Navotas	120.957491	14.643937	0.6	0–4.5	SM
						4.5–9	CL
						9–15	SC
8	Tanza Elementary School	Navotas	120.933461	14.679129	2.0	0–3	SC
						3–4.5	ML
						4.5–6	GP
						6–7.5	CL
						7.5–9	SC
						9–10.5	MH
						10.5–12	CL
						12–13.5	ML
						13.5–15	CL
15–18	SM						
18–20	GC-GM						
9	Dagat-Dagatan Elementary School	Navotas	120.956282	14.651251	0.3	0–1.5	CH
						1.5–6	SC-SM
						6–12	CH

Table 1. Cont.

Site No.	Name	City	Long. (°)	Lat. (°)	Water Table Depth (m)	Depth (m)	Soil Type (USCS)
10	Malabon Elementary School	Malabon	120.940551	14.677009	1.0	0–4.5 4.5–12 12–15	SP-SM ML CL
11	Panghulo Elementary School	Malabon	120.957800	14.684380	0.5	0–1.5 1.5–6 6–7.5 7.5–9 9–10.5 10.5–13.5 13.5–16.5 16.5–18 18–20	SP-SM SM CH CL CH MH CH MH CH
12	Imelda Elementary School	Malabon	120.960990	14.648665	1.2	0–3 3–9 9–15	SM CL CH
13	Ninoy Aquino Elementary School	Malabon	120.960700	14.654450	0.2	0–3 3–7.5 7.5–15	SC SM SC
14	Epifanio Delos Santos Elementary School	Malabon	120.992414	14.575557	3.0	0–4.5 4.5–6	SC SM
15	Manuel A. Roxas High School	Manila	120.999027	14.582204	0.9	0–1.5 1.5–4.5 4.5–6 6–10.5 10.5–12 12–13.5 13.5–15	SP-SM CH ML SM CH SM CH
16	Rafael Palma Elementary School	Manila	121.005917	14.567431	2.5	0–3 3–4.5 4.5–7.5 7.5–9 9–10.5 10.5–12 12–13.5 13.5–15	CL SC SM SC SW-SM SM SW-SM SP-SM
17	Jose Rizal Elementary School	Pasay	120.997418	14.543973	3.5	0–1.5 1.5–3 3–6 6–7.5 7.5–12 12–13.5 13.5–16.5 16.5–18 18–19.5 19.5–21 21–22.5 22.5–24 24–25.5 25.5–30	GC SP SW SP-SM SM SC CH SM ML MH CH MH CH MH

Table 1. Cont.

Site No.	Name	City	Long. (°)	Lat. (°)	Water Table Depth (m)	Depth (m)	Soil Type (USCS)
18	Paranaque Science High School	Parañaque	120.994677	14.500793	0.7	0–1.5	GM
						1.5–3	GP
						3–4.5	SP-SM
						4.5–6	SM
						6–7.5	MH
						7.5–12	SM
						12–13.5	CL
						13.5–15	MH
19	Sto. Nino Elementary School	Parañaque	120.996088	14.503082	No data	0–1.5	SC
						1.5–3	SP-SM
						3–4.5	SM
						4.5–6	ML
						6–7.5	MH
						7.5–9	GC
						9–10.5	ML
						10.5–12	MH
20	Manuyo Elementary School	Las Piñas	120.985444	14.482353	1.0	12–13.5	CL
						13.5–15	CH
						0–1.5	SP-SM
						1.5–4.5	SW-SM
						4.5–6	SP
						6–7.5	SM
						7.5–9	SP-SM
						9–10.5	CL
						10.5–12	MH
						12–13.5	CL
						13.5–15	SC

3.2. Geophysical Investigations

In the country, the most popular method among geotechnical engineers for assessing the strength of soil at a site is through standard penetration testing. Cross- or downhole profiling is also common to obtain in situ measurements of shear wave velocity with depth. These techniques may be precise and can provide measurement at, typically, one-meter resolutions. However, these methods can also rather be difficult and expensive to carry out in urban areas, as they require borehole drilling. Hence, non-invasive geophysical techniques are also utilized to overcome the problems posed by the practicality of borehole drilling. Seismic exploration techniques, e.g., multichannel analysis of surface waves (MASW), spectral analysis of surface waves (SASW), and refraction microtremors (hereafter “ReMi”) are relatively more economical, faster, and can be performed in a variety of sites, including urban areas. This study utilized ReMi surveys to derive one-dimensional shear wave velocity profiles of the surveyed sites in Metro Manila.

The ReMi technique was first developed by Louie (2001) [47], to demonstrate the application of ambient noise in determining the shallow shear wave velocity structure of a site. The idea behind this technique is that the vertical component of ambient noise, primarily dominated by Rayleigh waves that are caused by human activities, can be picked up by a geophone array.

In this study, ReMi surveys were performed at the twenty sites in Metro Manila where the SPT investigations were performed. The surveys are done by coupling a straight linear array of twelve vertical geophones into the ground. These geophones have a frequency of 4.5 Hz and were arranged to have a spacing that ranged from four to eight meters. The array was then connected to a DAQLink II multichannel recorder to gather thirty iterations of thirty seconds unfiltered noise. The sampling rate of the recording was set at

2 ms (500 Hz). In the surveyed sites, typical sources of noise include pedestrians, vehicle traffic, construction, and wind. To provide high frequency noise for the recordings, a 10 lbs. sledgehammer was introduced, to hit a 6 inches $\times$ 6 inches $\times$ 1 inch steel plate placed at each end of the array, and which was utilized as an active noise source.

Data processing was done using ReMi Vspect and ReMi Disper modules. The Rayleigh waves were identified from other wave arrivals using slowness-frequency (p-f) transforms of the noise recording, using the ReMi Vspect module. The fundamental mode phase velocity was chosen along the minimum velocity envelope of energy within the p-f domain. Louie (2001) [47] demonstrated that selecting along this trend is the best procedure for choosing a dispersion curve to obtain the best estimate of the true phase velocities of shear waves (Figure 2A). The ReMi Disper module allows the modelling of a dispersion curve with multiple layers and shear wave velocities, to match the dispersion curve of the field data. The modeler varies the layer thickness and velocities until the resulting dispersion curve matches the previously selected dispersion points (Figure 2B,C).

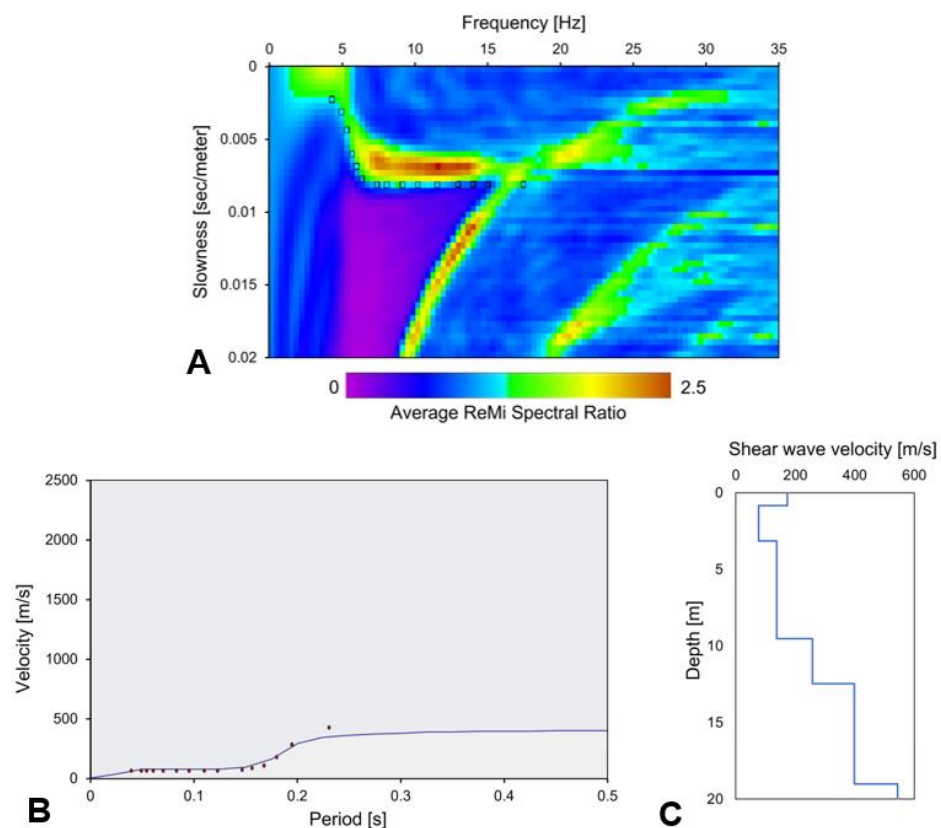


Figure 2. (A) Sample of a generated p-f image from the ReMi surveys and the identified dispersion curve and picks (black box) in the ReMi Vspect module. (B) Fitting of dispersion curve model into the dispersion picks in the ReMi Disper module. (C) Corresponding one-dimensional shear wave velocity profile from the dispersion curve model.

Vertical variations of shear wave velocities on the upper 20 m of the sites are illustrated in Figure 3. For most of the sites, the shear wave velocity of the upper 20 m generally ranged from ~ 100 m/s to ~ 220 m/s, corresponding to SPT-N values typically ranging from 2–10. For sites with much stiffer strata, the V_s at some depths can reach up to ~ 250 m/s to ~ 500 m/s. This was in areas with higher recorded N-values, that ranged from 15 to 50. In terms of the average V_s of the upper 30 m of the sites (V_{s30}), most of the western portion of Metro Manila was classified into Site Class D, based on the scheme of the National Structural Code of the Philippines [48]. This indicates that the area is generally underlain by stiff soil material, with a V_{s30} ranging from 180–360 m/s. This was also observed in the

data obtained from the refraction microtremor surveys, as the V_{s30} of the sites mostly fell in the Site D range.

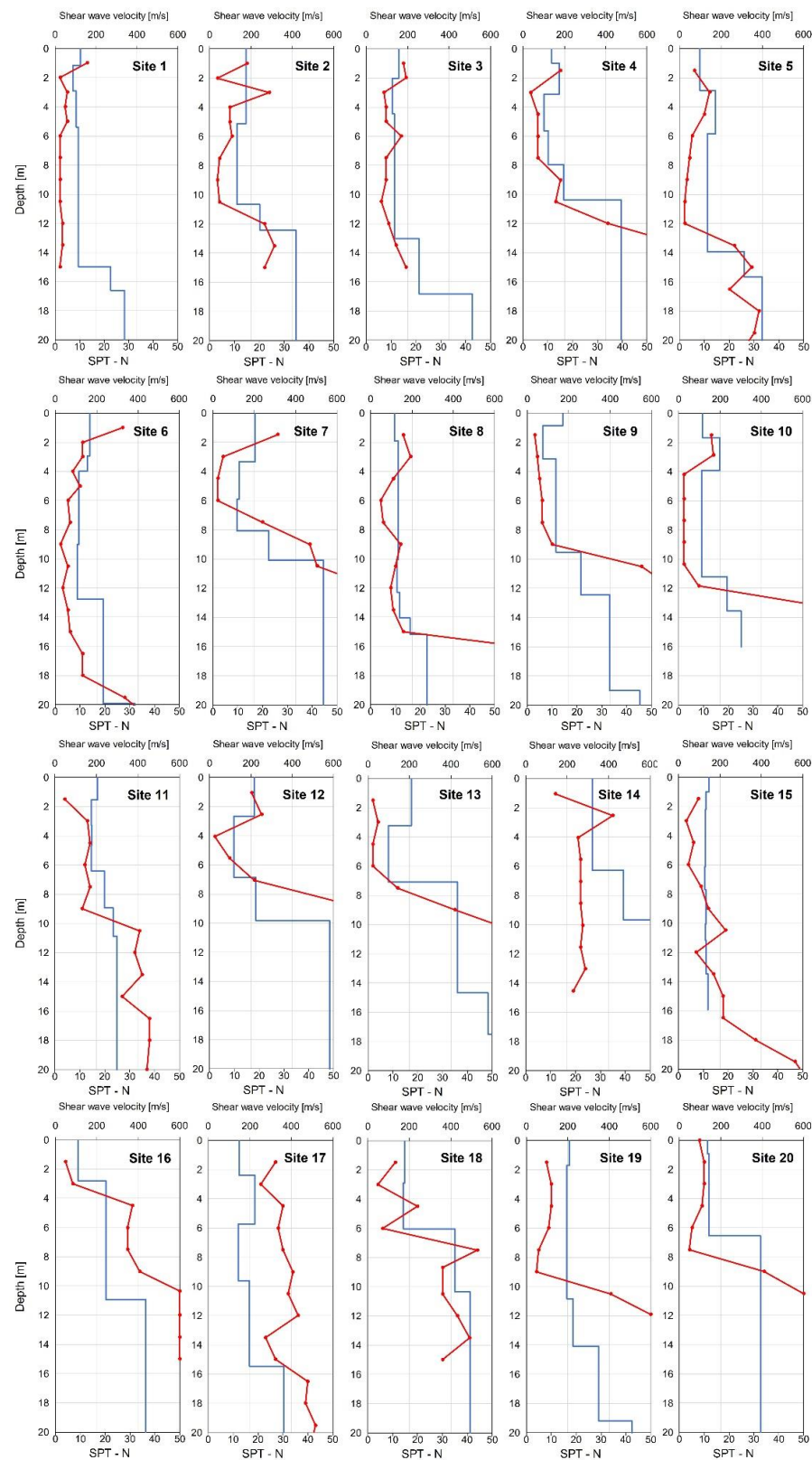


Figure 3. Variation of shear wave velocity (V_s) and penetration resistance (SPT-N) with depth for all twenty sites. Legend: blue lines for shear wave velocities; red lines for SPT-N values.

4. Methodology

A regression analysis is a statistical technique employed for analyzing empirical relationships between a dependent variable and one or more independent variables. This technique can be primarily applied to infer a relationship between the dependent and independent variable in a fixed dataset. It can also help in the visualization of variation of the values of the dependent variable, when one of the independent variables is adjusted while keeping the other independent variables constant. A particular type of regression analysis, the non-linear regression technique involves the modelling of the observed dependent variables using a mathematical function that combines one or more independent variables in a non-linear function. Power functions, exponential functions, logarithmic functions, and trigonometric functions are several typical examples of non-linear regression functions.

In this research, a power function was employed to correlate the estimated shear wave velocities, to measure the SPT-N values. This non-linear function is widely utilized in rapid evaluation of V_s and associated geotechnical parameters. The power function has a basic form of

$$E(x, y) = ax^b \quad (1)$$

where x and y are two variables, with x as the independent variable and where y is the response variable, while a and b are parameters of the power function [49]. a is a constant controlling the amplitude of the function, and b controls the relationship curve. This research examined the correlation based upon corrected and uncorrected SPT-N values and the V_s , irrespective of the depth, overburden pressure, geologic age of the deposit, and fines content.

Applying the natural logarithm function to Equation (1) transforms the non-linear function into a linear regression equation with the form

$$Y' = b_0 + b_1 X' \quad (2)$$

where $Y' = \ln y$, $b_0 = \ln a$, $b_1 = b$, and $X' = \ln x$. The parameters of regression b_0 and b_1 are determined using the least squares method

$$b_1 = \frac{\sum_{i=1}^n x_i y_i - \frac{1}{n} \sum_{i=1}^n x_i \sum_{i=1}^n y_i}{\sum_{i=1}^n x_i^2 - \frac{1}{n} (\sum_{i=1}^n x_i)^2} \quad (3)$$

$$b_0 = \frac{1}{n} \sum_{i=1}^n y_i - \frac{b_1}{n} \sum_{i=1}^n x_i \quad (4)$$

with x_i substituted by $\ln x$, y_i by $\ln y$, and n as the number of data points. When the values of b_0 and b_1 are determined, then the original parameters of the power function at Equation (1), a and b , can be also be calculated.

To measure the quality of the non-linear regression analysis, various statistical parameters need to be determined as well. The residual (ε_i) of the regression analysis is the difference from the observed value (y_i) of the dependent variable in comparison to its predicted value (y_i^*), using the regression function (Equation (5)).

$$\varepsilon_i = y_i - y_i^* \quad (5)$$

The total variability (S_{YY}) of the dependent variable (y_i) is determined from two components: the (1) variability in the observations of the y_i , which is accounted for by the regression function (SS_R); and the (2) residual variation, which is left unexplained by the regression function (SS_E) [49]. The method of determining S_{YY} is shown in Equations (6) and (7). In these equations, $\bar{y}$ is the average of the observed values of the dependent variable.

$$S_{YY} = SS_R + SS_E \quad (6)$$

$$\sum_{i=1}^n (y_i - \bar{y})^2 = \sum_{i=1}^n (y_i^* - \bar{y})^2 + \sum_{i=1}^n (y_i - y_i^*)^2 \quad (7)$$

The coefficient of regression (R^2) is the fraction of the total variability in the dependent variable that is accounted for by the regression function. This has a value that ranges from 0 to 1 and is expressed as

$$R^2 = \frac{SS_R}{S_{YY}} = \frac{\sum_{i=1}^n (y_i^* - \bar{y})^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (8)$$

To define the strength and nature of relationship between the dependent and independent variables, the coefficient of correlation (r) is also determined [49,50]. This value is expressed as

$$r(x, y) = \frac{\frac{1}{n} \left[\sum_{i=1}^n x_i y_i - \frac{\sum_{i=1}^n x_i \sum_{i=1}^n y_i}{n} \right]}{\sqrt{\frac{\sum_{i=1}^n x_i^2}{n} - \left(\frac{\sum_{i=1}^n x_i}{n} \right)^2} \sqrt{\frac{\sum_{i=1}^n y_i^2}{n} - \left(\frac{\sum_{i=1}^n y_i}{n} \right)^2}} \quad (9)$$

Another method to examine the quality of the obtained correlation is to determine Spearman's rank correlation coefficient (r_s) [50,51]. This non-parametric measure of correlation utilizes ranks to measure the correlation between an independent and response variable. The ordered datasets are replaced by rankings and the correlation coefficient (r_s) is calculated on the ranks, measuring the strength of association between the two ranked variables. This coefficient indicates how closely two sets of rankings agree with each other. r_s is obtained using the equation

$$r_s = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)} \quad (10)$$

where d_i is the difference between the ranks and n is the number of members for each parameter. For the purposes of this work, the smallest value of each parameter (i.e., SPT N-values, shear wave velocities) was assigned with rank 1, and the rest of the dataset were ranked subsequently, in increasing order. Identical values in a dataset were assigned a rank equal to the average of their positions in the ascending order of values.

Aside from calculating different statistical parameters, graphical analysis of residuals can also be used to evaluate the proposed correlations. Histograms of standardized residuals can identify potential outliers and can determine whether the variance is normally distributed. A probability–probability (p-p) plot compares the empirical cumulative distribution function with a theoretical cumulative distribution function. p-p plots can determine if a model follows the assumed normality, as the points must follow the 1:1 diagonal line to be normally distributed data.

5. Results and Discussion

Several empirical relations of shear wave velocity (V_s) and penetration resistance (N) have been developed by a variety of researchers. In some references, corrected N-values were used in the regression analysis. These empirical correlations are summarized in Table 2. These correlations have a basic power law form $V_s = a \times N^b$, where a and b are coefficients that govern the shape of the empirical function. From Table 2, it is observable that for all previously proposed empirical correlations, a typically ranges from 19 to 121 and b ranges from 0.24 to 0.85.

Table 2. Existing correlation between shear wave velocity and standard penetration resistance.

Author	All Soils	Sand	Silt	Clay
Kanai (1966) [52]	$V_s = 19N^{0.6}$	-	-	-
Shibata (1970) [10]	-	$V_s = 31.7N^{0.54}$	-	-
Imai and Yoshimura (1970) [8]	$V_s = 76N^{0.33}$	-	-	-
Ohba and Toriumi (1970) [9]	$V_s = 84N^{0.31}$	-	-	-
Ohta et al. (1972) [11]	-	$V_s = 87.2N^{0.36}$	-	-
Fujiwara (1972) [12]	$V_s = 92.1N^{0.337}$	-	-	-
Ohsaki and Iwasaki (1973) [13]	$V_s = 81.4N^{0.39}$	-	-	-
Imai et al. (1975) [53]	$V_s = 89.9N^{0.341}$	-	-	-
Imai (1977) [14]	$V_s = 91N^{0.337}$	$V_s = 80.6N^{0.331}$	-	$V_s = 80.2N^{0.292}$
Ohta et al. (1978) [54]	$V_s = 85.35N^{0.348}$	-	-	-
Seed and Idriss (1981) [16]	$V_s = 61.4N^{0.5}$	-	-	-
Imai and Tonouchi (1982) [15]	$V_s = 96.9N^{0.314}$	-	-	-
Seed et al. (1983) [55]	-	$V_s = 56.4N^{0.5}$	-	-
Sykora and Stokoe (1983) [18]	-	$V_s = 100.5N^{0.29}$	-	-
Fumal and Tinsley (1985) [56]	-	$V_s = 152 + 51N^{0.27}$	-	-
Tonouchi et al. (1983) [57]	$V_s = 97N^{0.314}$	-	-	-
Jinan (1987) [58]	$V_s = 116 (N + 0.3185)^{0.6}$	-	-	-
Okamoto et al. (1989) [59]	-	$V_s = 125N^{0.3}$	-	-
Lee (1990) [60]	-	$V_s = 57.4N^{0.49}$	$V_s = 105.64N^{0.319}$	$V_s = 114.43N^{0.31}$
Athanasopoulos (1995) [23]	$V_s = 107.6N^{0.36}$	-	-	$V_s = 76.55N^{0.445}$
Yokota et al. (1981) [61]	$V_s = 121N^{0.27}$	-	-	$V_s = 114N^{0.31}$
Kalteziotis et al. (1992) [21]	$V_s = 76.2N^{0.24}$	-	-	-
Pitilakis et al. (1992) [62]	-	$V_s = 162N^{0.17}$	-	-
Raptakis et al. (1995) [24]	-	$V_s = 100.7N^{0.24}$	-	-
Sisman (1995) [63]	$V_s = 32.8N^{0.51}$	-	-	-
Iyisan (1996) [26]	$V_s = 51.5N^{0.516}$	-	-	-
Kayabali (1996) [27]	-	$V_s = 175 + (3.75N)$	-	-
Jafari et al. (1997) [64]	$V_s = 22N^{0.85}$	-	-	-
Pitilakis et al. (1999) [22]	-	$V_s = 145 (N_{60})^{0.178}$	-	$V_s = 132 (N_{60})^{0.271}$
Kiku et al. (2001) [65]	$V_s = 68.3N^{0.292}$	-	-	-
Jafari et al. (2002) [66]	-	-	$V_s = 22N^{0.77}$	$V_s = 27N^{0.73}$
Hasancebi and Ulusay (2007) [28]	$V_s = 90N^{0.309}$	$V_s = 90.82N^{0.319}$	-	$V_s = 97.89N^{0.269}$
Hasancebi and Ulusay (2007) [28]	$V_s = 104.8 (N_{60})^{0.26}$	$V_s = 131 (N_{60})^{0.205}$	-	$V_s = 107.6 (N_{60})^{0.237}$
Dikmen (2009) [30]	$V_s = 58N^{0.39}$	$V_s = 73N^{0.33}$	$V_s = 60N^{0.36}$	$V_s = 44N^{0.48}$
Uma Maheswari et al. (2010) [35]	$V_s = 95.64N^{0.301}$	$V_s = 100.53N^{0.265}$	-	$V_s = 89.3N^{0.358}$
Fauzi (2014) [67]	$V_s = 105.03N^{0.286}$	-	-	-

5.1. All Soils

This study utilized 265 data pairs from 20 sites in Metro Manila to propose new V_s – N empirical correlations for all soil types (Figure 4A). The empirical correlations were developed using non-linear regression analysis to fit the power law form. The proposed correlation from the data of this study is

$$V_s = 56.82N^{0.4861} \quad (11)$$

This relation has a regression coefficient $R^2 = 0.7515$, which indicates a strong correlation between the datasets [68]. Empirical correlations for the soil types proposed by other researchers were also compiled and compared to the results of this study (Figure 4C). In this compilation, for correlations that follow the form $V_s = a \times N^b$, the values of a range from 19 to 121 and b ranges from 0.24 to 0.85 can be observed. Among the compiled research that published empirical correlations, only Hasancebi and Ulusay (2007) [28] utilized corrected SPT- N values. On the other hand, Jinan (1987) [58] also proposed a correlation with a form $V_s = a (N + b)^c$.

It can be observed that the correlation by Kanai (1966) [52] can be used as the lower bound, while the work of Athanasopoulos (1995) [23] and Jafari et al. (1997) [64] provide a suitable upper bound for the proposed empirical relation of this study. The other twenty-one correlations were constrained by these three functions. Furthermore, the proposed curve of the present study lies closest to that proposed by Iyisan (1996) [26].

This study also explored correlating the shear wave velocity to corrected SPT-N values by applying several correction factors (Figure 4B). These correction factors are for the rod length (C_R), sampling method (C_S), borehole diameter (C_B), energy ratio (C_E), and overburden pressure (C_N). There are different equations for the correction of SPT-N values (N_1)₆₀, but the equation applied in this work is as follows:

$$N_{60} = N \times C_R \times C_S \times C_B \times C_E \quad (12)$$

$$(N_1)_{60} = N_{60} \times C_N \quad (13)$$

For overburden pressure correction, we adapted the equation proposed by Kayen et al. (1992) [69], which is as follows:

$$C_N = \frac{2.2}{1.2 + \frac{\sigma'_{vo}}{P_a}} \quad (14)$$

σ'_{vo} is the effective overburden pressure at the depth in kPa, and P_a is the reference pressure equal to 100 kPa. Rod length correction (C_R) was applied using the factors provided by Youd et al. (2001) [70]. A sampling method (C_S) correction factor of 1 was used, as most SPT drillings in the Philippines utilize standard samplers. Borehole diameter (C_B) and energy ratio (C_E) factors were applied following the scheme of Skempton (1986) [71]. After the application of these correction factors, non-linear regression analysis was employed again, to determine the empirical function to correlate V_s and corrected SPT-N values.

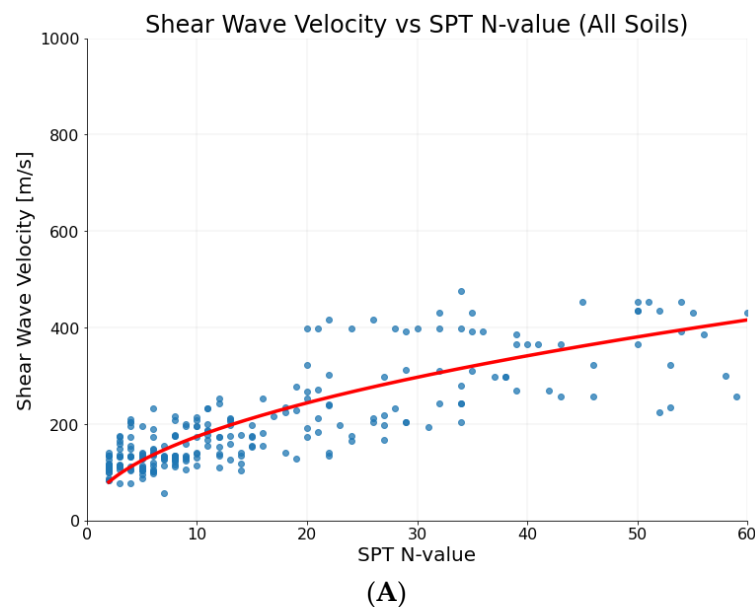


Figure 4. Cont.

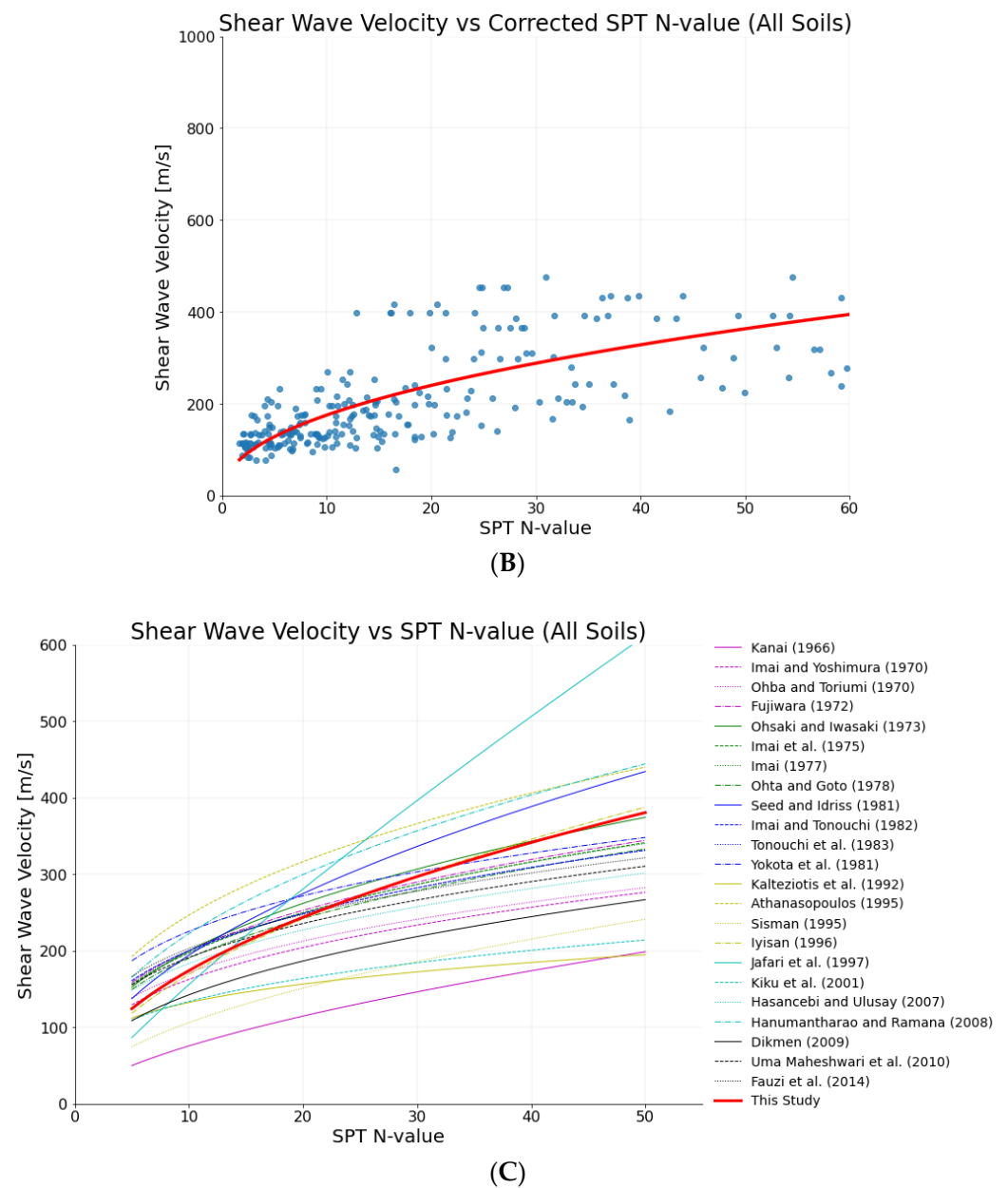


Figure 4. (A). Uncorrected SPT-N and V_s pairs for all soils and the determined empirical correlation. (B). Corrected SPT-N and V_s pairs for all soils and the determined empirical correlation. (C). Comparison of the proposed empirical correlation for all soil types and other published works [8,9,12–16,21,23,26,28,30,34,35,52,53,57,61,63–65,67,72].

The determined correlation from the data is

$$V_s = 61.77(N_1)_{60}^{0.4528} \quad (15)$$

This relation has a regression coefficient $R^2 = 0.5685$, indicating a moderate correlation, which is slightly lower than the regression coefficient when uncorrected SPT-N values are used in the analysis. This suggests that uncorrected SPT-N values correlate shear wave velocity better than corrected values.

5.2. Sandy Soils

A similar non-linear regression analysis was applied for sandy soil materials. Out of the 265 data points, 139 were identified to be of sandy soil. The proposed correlation for sandy soil types is

$$V_s = 45.07N^{0.5534} \quad (16)$$

This proposed correlation has a coefficient of regression value of $R^2 = 0.7922$. This value is relatively higher than the coefficient for all soil types and can be regarded as a strong correlation [68]. Figure 5 shows the plotted V_s and N -value for sandy soil and the corresponding proposed empirical relation. The empirical correlations for sandy soils proposed by other researchers were also compiled. Thirteen correlations follow the power law form $V_s = a \times N^b$ while utilizing the uncorrected SPT-N values in the analysis, while Pitilakis et al. (1999) [22] and Hasancebi and Ulusay (2007) [28] utilized corrected N -values for their statistical analysis. From the compiled curves, the a coefficient ranges from 31.7 to 162, while the b coefficient ranges from 0.17 to 0.54. On the other hand, Fumal and Tinsley (1985) [56] and Kayabali (1996) [27] proposed an empirical relation with the form $V_s = a(N + b)^c$.

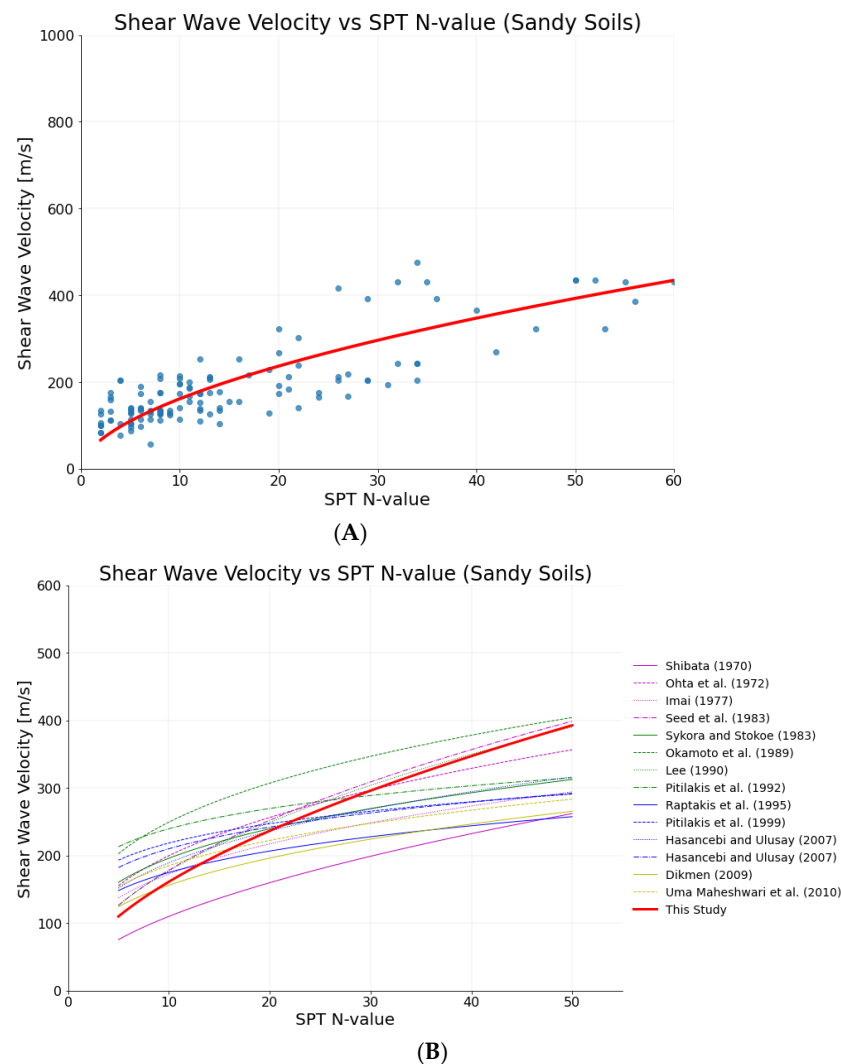


Figure 5. (A). Uncorrected SPT-N and V_s pairs for sandy soils and the determined empirical correlation. (B). Comparison of the proposed empirical correlation for sandy soil types and other published works [10,11,14,18,22,24,28,30,35,55,59,60,62].

When the proposed empirical relation is compared to the works of other researchers, it can be observed that the relations proposed by Okamoto et al. (1989) [59] and Shibata (1970) [10] can act as the upper and lower limits for empirical relationships for sandy soil types, respectively. The other eleven published empirical relations lie between these constraints, including the one proposed by this study. As the curve of this present study lies in the middle of all the other curves, this indicates a very good agreement with respect to the previous works.

5.3. Clayey Soils

A non-linear regression analysis was also applied to clayey soil types. A total 120 data pairs of V_s -SPT-N values were identified and utilized for the statistical analysis. The proposed correlation for clayey soil in this study is

$$V_s = 70.26N^{0.4220} \quad (17)$$

This proposed correlation has a coefficient of regression value of $R^2 = 0.73$. This value is relatively lower than the coefficient for all soil types but can still be regarded as having a strong correlation [68]. Figure 6 illustrates the plotted data pairs of V_s and N-values for clayey soil and the corresponding empirical relations. Empirical relations proposed by other authors were also compiled and compared. Eight correlation functions used the basic power law function while incorporating uncorrected SPT-N values in the analysis. In this compilation, coefficient a ranges from 27 to 114.43, and coefficient b ranges from 0.217 to 0.73.

It can be observed from the compiled empirical curves for clayey soils that the functions by Pitilakis et al. (1999) [22] and Athanasopoulos (1995) [23] can serve as the upper bound of the proposed relations, with the curve of Pitilakis et al. (1999) [22] for N values less than 22 and N values greater than 22 for Athanasopoulos (1995) [23]. For the lower bound, the curve by Dikmen (2009) [30] can be applied for N-values less than 24. Further constraints by Imai (1977) [14] can be applied as a lower bound for N-values greater than 24. The other empirical relations lie within these boundaries, including the one proposed in this study for clayey soils. As this curve lies in the middle of the other published curves, this is an indication of the good agreement between the proposed relation and the other published works. It can also be noticed that the curve proposed by this study lies close to the work by Uma Maheshwari et al. (2010) [35].

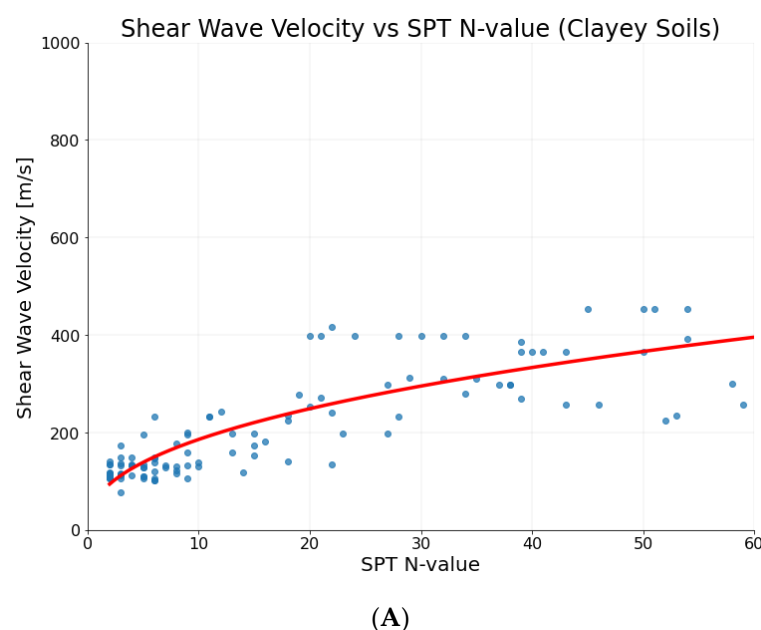


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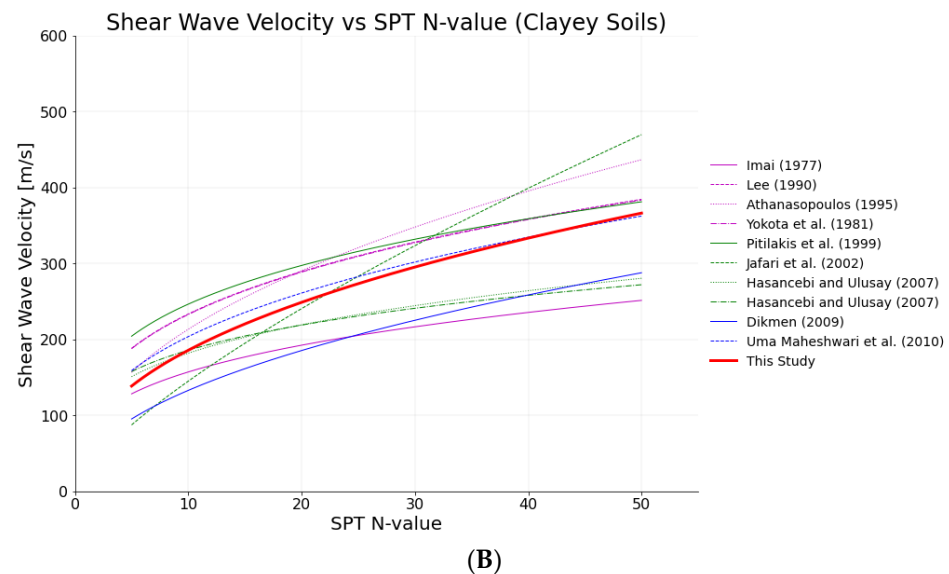


Figure 6. (A). Uncorrected SPT-N and V_s pairs for clayey soils and the determined empirical correlation. (B). Comparison of the proposed empirical correlation for clayey soil types and other published works [14,22,23,28,30,35,60,61,66].

5.4. Statistical Evaluation

Several methods were used to evaluate the proposed V_s -SPT-N values empirical relationships for all, sandy, and clayey soil types (Table 3). From the regression analysis, evaluated regression lines have an R^2 that ranges from 0.73 to 0.80, suggesting a moderate to strong fit of the proposed empirical function to the obtained dataset. Evaluation using the coefficient of correlation (r) and the Spearman rank coefficient (r_s) suggested that there is moderate to strong correlation between the V_s and SPT-N values from the dataset.

Table 3. Summary of the proposed correlations from this study.

Soil Type	Proposed Correlation	Coefficient of Regression (R^2)	Coefficient of Correlation (r)	Spearman Rank Correlation (r_s)
All soils	$V_s = 56.82N^{0.4861}$	0.7515	0.8767	0.8424
Sandy soil	$V_s = 45.07N^{0.5534}$	0.7922	0.9050	0.8192
Clayey soil	$V_s = 70.26N^{0.4220}$	0.7334	0.8453	0.8493

An alternative method applied to evaluate the validity of the proposed empirical relations was through an analysis of the residuals. Graphical methods for analyzing the residuals applied in this research included the development of residual histograms and probability–probability (p-p) plots (Figure 7). Histogram plots of the residuals determined whether the variance of the datasets was normally distributed. An ideal histogram of the residuals, which follows a bell-shaped distribution and which is distributed around zero, suggests that the normality assumption is likely true. In this analysis, histograms were produced from standardized residual values, which is solely the raw residual divided by its standard error. The method of standardizing residuals is applied to transform data, such that its mean centers at zero and the standard deviation equals one. This technique also identified potential outliers, such that residuals with standard deviations less than -3 or greater than 3 , could be identified. In this analysis, histograms from the datasets suggested that the residuals generally followed a normal distribution, and outliers with standard deviations greater than $|3|$ were not detected.

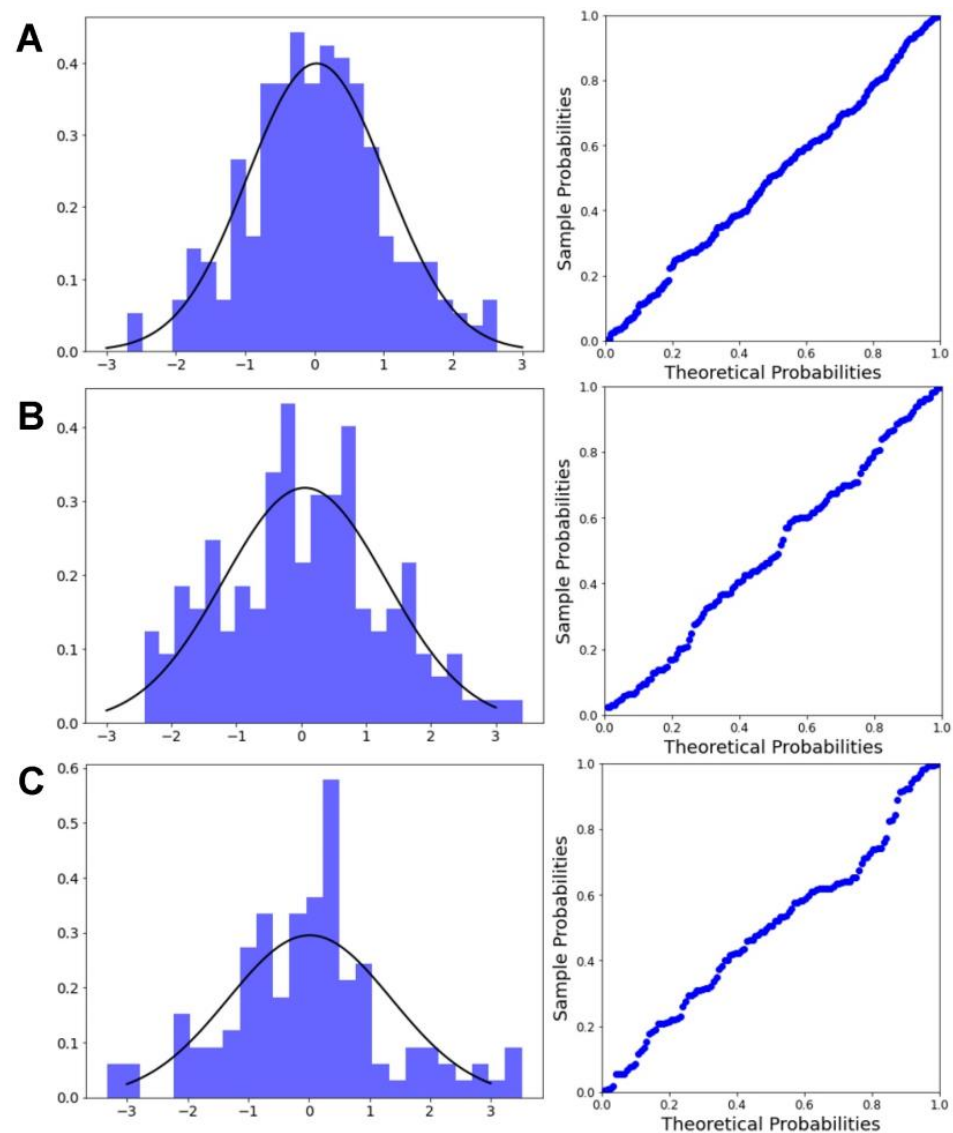


Figure 7. Histogram of the standardized residuals and the probability–probability (p-p) plots for (A) all soils, (B) sandy soils, and (C) clayey soils.

The second graphical technique applied was a p-p plot. This type of plot compares the empirical cumulative distribution function with the theoretical cumulative distribution function. Moreover, this plot can also show whether the residuals or errors follow the assumed normality. Points on the p-p plot must follow the 1:1 diagonal line for normally distributed data.

Finally, the measured V_s and estimated V_s from each empirical correlation were compared, in order to assess the performance of the regression models (Figure 8). Data pairs mostly lay in the region between the lines 1:1.50 and 1:0.65.

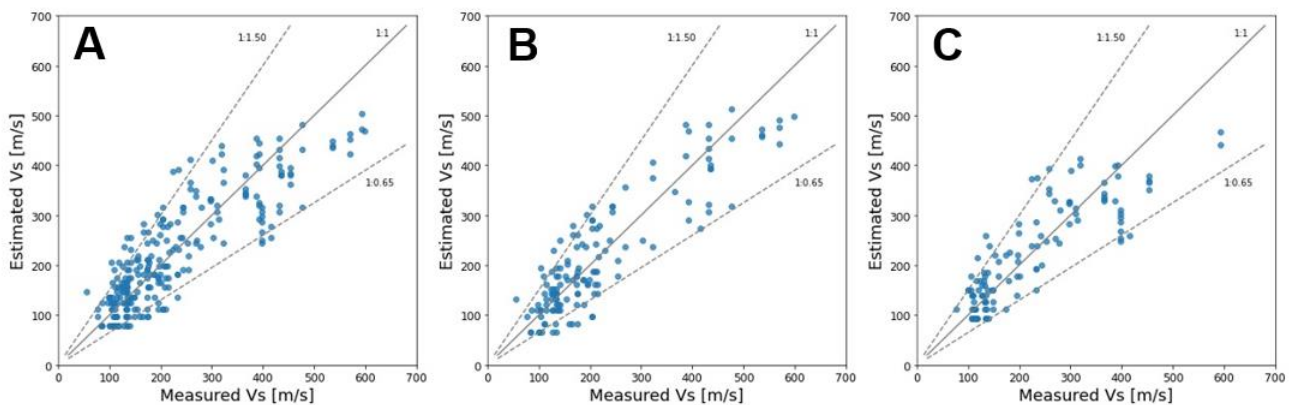


Figure 8. Measured versus estimated V_s for (A) all soils, (B) sandy soils, and (C) clayey soils with lines of 1:1.5, 1:1 and 1:0.65.

5.5. Application for Site-Specific Characterization

One of the main applications of these empirical correlations is the estimation of the average shear wave velocity of the upper 30 m of a site (V_{s30}). This metric is generally used for the classification of sites into the general characteristic of the subsurface, for earthquake engineering design. In the Philippines, V_{s30} is the most important parameter needed for the site classification scheme stipulated by the National Structural Code of the Philippines (2015) [44]. This scheme classifies a site into six categories used for earthquake engineering design (Table 4).

Table 4. Site classification scheme according to the National Structural Code of the Philippines, employing the V_{s30} metric to determine the general soil description and its typical corresponding N-values.

Soil Profile Type	Soil Profile Description	Shear Wave Velocity, V_s , (m/s)	SPT-N (Blows/30 cm)
S_A	Hard Rock	>1500	-
S_B	Rock	760–1500	-
S_C	Very Dense Soil and Soft Rock	360–760	>50
S_D	Stiff Soil	180–360	15–50
S_E^1	Soft Soil	<180	<15
S_F	Soil requiring site-specific evaluation		

¹ Soil profile type S_E also includes any soil profile with more than 3.0 m of soft clay defined as soil with plasticity index > 20, moisture content $\geq 40\%$, and undrained shear strength < 24 kPa.

The magnitude of V_{s30} can be computed in accordance with the expression

$$V_{s30} = \frac{30}{\sum_{i=1}^n \frac{h_i}{v_i}} \quad (18)$$

where h_i and v_i are the layer thickness (m) and shear wave velocity (m/s) of the i th layer, respectively, in a total of n layers existing in the top 30-m of a site. The magnitude of the V_s is estimated from SPT-N values using the proposed empirical relations applicable for all soil types. Sample boreholes with penetration depths reaching 30 m were examined, and the proposed empirical correlation was applied to the datasets (Table 5). The calculated V_{s30} s highlight the site classifications obtained from SPT data. Site Class D classification is dominant in Metro Manila, particularly on the western sector of the region along the coast. This suggests that the sites are generally underlain by stiff soil deposits. This is further supported by the Quaternary Alluvium deposits mapped along the western coast, proximal to Manila Bay.

Table 5. Typical average shear wave velocity to a 30-m depth (V_{s30}) of all soils at various locations in Metro Manila.

Location	Coordinates	Generalized Soil Profile Description	V_{s30} Using Proposed Correlation for All Soil Types	Site Class Per NSCP (2015)
J. A. Santos High School, Manila City	120.972674° E, 14.597179° N	poorly graded to silty sand, silt	187.30	Class D
T. Paez Elementary School, Manila City	120.966613° E 14.630679° N	silt, well-graded and silty sand	243.10	Class D
Amang Rodriguez Elementary School, Malabon City	120.949242° E 14.671821° N	silty gravel, silty sand, clays	320.08	Class D
Tangos I Elementary School, Navotas City	120.932371° E 14.673729° N	poorly graded to silty sand, silt	274.71	Class D
Jose Rizal Elementary School, Pasay City	120.997418° E 14.543973° N	well graded to silty sand, silt	330.05	Class D
V.E. Fugoso Memorial Elementary School, Marikina City	121.118325° E 14.666042° N	high plasticity silt, low plasticity clay	225.04	Class D

An additional utility of these correlations is in the refinement of the corresponding N-values for a specific range of shear wave velocities. Based on the outcomes of this study, a simplified correlation can be established for basic soil strength classification (i.e., soft soils, stiff soils, and very dense soils) (Table 6).

Table 6. Simplified correlation of V_s and SPT-N for different soil strength classifications in this study.

Soil Description	V_s (m/s)	SPT N-value
Very soft to soft soils	<180 m/s	<10
Stiff soils	180–360 m/s	10–45
Very dense soils	360–760 m/s	>45

This demonstrates the utility of the proposed empirical correlations for geotechnical description at site-specific scales, as well as seismic microzonation efforts in the study area. Specific ranges of V_s have a corresponding range of N-values, where geophysical measurements of V_s can complement point borehole profiles and establish the lateral continuity of subsurface material between drilling points. In situations where SPT boreholes might not be feasible, due to economic or logistic reasons, refraction microtremor or other geophysical tests that can reliably measure shear wave velocities and can serve as a proxy to determine the relative strength of soils, especially for smaller construction projects. This was demonstrated by Pancha and Apperley (2021) [73], through utilizing refraction microtremors in two-dimensional shear wave velocity mapping, thereby extending subsurface characterization and mapping lateral variations between spot boreholes.

Alternatively, shear wave velocity surveys might not be feasible in some urban areas, due to a lack of availability of open space to lay the linear geophone array, which is a technical requirement of some geophysical tests. These sites instead might have robust borehole survey results acquired before the building's construction. Compilation of these SPT datasets can be utilized and converted to shear wave values, to produce or refine seismic microzonation maps. The derived empirical correlations of V_s and reliable static field data such as the SPT N-value can be an alternative way to determine these seismic parameters, such as the V_{s30} .

However, an important caveat, before the application of the proposed empirical relations, is to ensure the reliability of obtained SPT data to estimate the corresponding V_s values. On the other hand, the processing of geophysical data to acquire V_s must also be performed with utmost caution, to minimize uncertainty before applying it for basic soil strength classification. Furthermore, these empirical correlations must be applied with

caution and with consideration to the geologic, geomorphologic, and geotechnical setting of an area. Areas with a very different environment must utilize other empirical functions that are more suitable to the locality.

6. Conclusions

By utilizing 265 pairs of SPT-N values and V_s , empirical relations between the two variables were developed for the area of Metro Manila, Philippines. Data from field surveys using standard penetration tests and refraction microtremor were obtained in 20 sites in Metro Manila, all situated along the western coast of the region and underlain by unconsolidated Quaternary Alluvium deposits. These datasets were mainly grouped into three: all soils, sandy soils, and clayey soil types. New empirical relations were determined using non-linear regression analysis. To evaluate the statistical validity of the empirical models, parameters such as coefficient of regression (R^2), coefficient of correlation (r), and Spearman rank correlation (r_s) were determined for each soil grouping. The determined values from these coefficients (R^2 : 0.73–0.79, r : 0.84–0.90, r_s : 0.81–0.85) suggested a moderate to strong correlation between the two parameters. Moreover, residual histograms and probability–probability plots were also produced, to graphically analyze the datasets and evaluate the proposed empirical functions. This analysis showed the presumed normality distribution of the residuals and therefore supported the validity of the empirical models. The newly developed empirical correlations for the three categories of soil are comparable to other works on this subject by researchers around the world. This suggests that the new correlations can be applied for site-specific seismic characterizations. This was demonstrated by estimating magnitudes of V_{s30} from SPT-N values, which were consistent with pre-identified site classifications. This shows the utility of the proposed correlations for seismic microzonation efforts in the study area, as long as there are reliable SPT values.

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