applied sciences

Article

Determination of Empirical Correlations between Shear Wave Velocity and Penetration Resistance in the Canakkale Residential Area (Turkey)

Mehmet Celal Tunusluoglu

Department of Geological Engineering, Canakkale Onsekiz Mart University, Terzioglu Campus,
17020 Canakkale, Turkey; ctunus@comu.edu.tr

Abstract: One of the most important parameters used to determine the dynamic properties of soil layers is the shear wave velocity. In geotechnical earthquake engineering, the shear wave velocity is used to determine the shear modulus, which provides the input parameters for the design of earthquake-resistant structures. Although there are measurement methods used in field studies to determine the shear wave velocity, they may not be economical in some cases. In this study, the empirical correlations between the shear wave velocity and penetration resistance in sandy soils were investigated with the use of geotechnical and geoseismic data obtained within the scope of microzonation studies performed in the Canakkale residential area. The results of the study were compared with correlations obtained from previous studies, and the equation we produced showed a good ability to predict the shear wave velocity. In addition, it was determined that standard penetration resistance, without energy correction, provided a better correlation coefficient.

Keywords: shear wave velocity; standard penetration test; seismic refraction; correlation equation; Canakkale

Citation: Tunusluoglu, M.C. Determination of Empirical Correlations between Shear Wave Velocity and Penetration Resistance in the Canakkale Residential Area (Turkey). *Appl. Sci.* **2023**, *13*, 9913. https://doi.org/10.3390/app13179913

Academic Editor: Sang-Hyo Kim

Received: 21 July 2023
Revised: 23 August 2023
Accepted: 29 August 2023
Published: 1 September 2023

1. Introduction

Earthquake damage generally occurs in structures built on soft sediments rather than firm bedrock. The most important factors that cause structural damage as a result of the seismic waves produced by earthquakes are the behavior and engineering properties of the layers in the soil profile where the building foundation is located. Whereas the amplitude of seismic waves increases as the seismic waves move through soft soils, the amplitude decreases in firm soils. The increase in the amplitude of seismic waves is defined as soil amplification. As the amplification effect of soil is a very important feature in terms of soil–structure interactions in earthquake-sensitive areas, it is extremely important to know the dynamic behavior of soils when designing earthquake-resistant structures. Seismic methods are used to determine these features in situ. These methods include generating elastic waves at small deformation levels, where soils exhibit elastic behavior, and detecting velocities from wave arrival times. As the wave propagation speed depends on the physical properties of the ground, the obtained seismic waves can provide information about the dynamic behavior of the soils. If the wave propagation velocities of the layers in any soil section are known, then other parameters showing soil behavior can be found based on these velocities. Through the use of seismic methods, the shear wave velocity (V_s) is measured at low deformation levels in the field. The shear wave velocity is a very important parameter in the field of geotechnical earthquake engineering. It is one of the most important input parameters for representing the stiffness of the soil layers [1–8]. Additionally, important engineering features in the ground, such as the small-strain shear modulus ($G_{\max}$), can be determined [9–16]. The small-strain shear modulus is calculated according to the following equation:

$$G_{\max} = \gamma V_s^2 \quad (1)$$

where γ is the total mass density of the soil.

However, there are several methods of measuring the shear wave velocity, which include both field and laboratory tests. The field tests have many advantages over the laboratory tests and are always preferable [14]. Field tests, such as the seismic reflection test, seismic refraction test, spectral analysis of surface waves (SASWs) test, multichannel analysis of surface waves (MASWs) test, and seismic cross-hole test are commonly used to determine the shear wave velocity [2]. The shear wave velocity determined via seismic methods can also be identified using the standard penetration test (SPT) blow count (SPT-N), for economic reasons. There are often difficulties in determining the V_s value for every location in the field, and overcoming these difficulties incurs both time and economic losses. Chatterjee and Choudhury [2] state that the determination of the shear wave velocity in the field is not often economically feasible in urban areas for microzonation studies. This is also due to the nonavailability of the free space that is necessary as per the technical requirements for such field tests. In addition, Chatterjee and Choudhury [2] noted that these tests are also not used, or are avoided, by many soil investigation agencies due to cost considerations, a lack of specialized personnel, and the high noise levels caused. For this reason, reliable empirical relationships between the SPT blow count (SPT-N) and V_s values are often preferred to speed up studies [1–8,17].

Canakkale, located in the northwest of Turkey, is one of the cities that has undergone rapid development in the last 15 years (Figure 1). During this rapid development, dangerous land with liquefaction potential has been zoned for development, often without urban planning, and without any soil stabilization precautions taken.

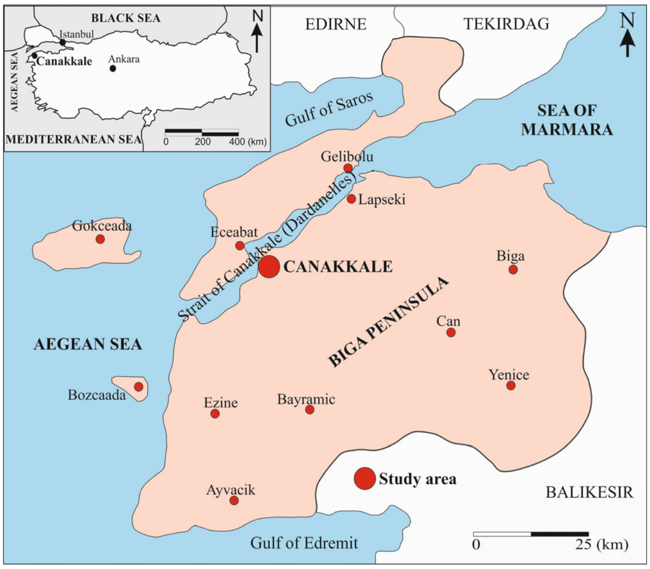

Figure 1. Location map of the study area.

The Canakkale residential area is largely located on Quaternary alluvial deposits carried by the Saricay stream. The average groundwater level in the alluvial deposits is approximately 2 m in Canakkale city center. Canakkale Province is located in an area of high seismic activity, according to the Turkey Earthquake Hazard Map [18]. The Municipality of Canakkale aimed to detect areas where soil stabilization should be implemented, by examining the ground conditions in the Canakkale settlement area. For this purpose, a microzonation study was performed in the Canakkale settlement area. Microzonation is a detailed and multidisciplinary study that aims to divide the area of study into zones with respect to its geological, geotechnical, geophysical, and geometrical characteristics, and to provide reliable maps of seismic ground-shaking parameters, considering local site effects, as well as induced hazards, such as liquefaction and landslides. A detailed microzonation study provides the basis for an advanced seismic risk assessment of an urban area, and for earthquake design considerations in new engineering projects [19].

Within the scope of this study, both geotechnical borehole studies and geophysical studies were carried out. In the geotechnical borehole studies, soil samples were taken with an SPT sampler and Shelby tube, the SPT test was applied, and the static groundwater level was identified. Within the scope of the geophysical studies, shear wave velocity data for the Canakkale settlement area were obtained via the seismic refraction method and multichannel surface wave analysis (MASWs) studies. Based on the results, the engineering and seismic parameters for the ground in the Canakkale settlement area were determined, the liquefaction potential was examined, and the areas where precautions must be taken were identified [20].

The main purpose of this article is to develop a regression equation between V_s and SPT-N as a result of the geotechnical and geophysical studies carried out on alluvial deposits in the Canakkale settlement area. More than two-thirds of the geotechnical borehole studies, seismic refraction, and MASWs studies carried out within the scope of the microzonation studies were performed on alluvial deposits. Statistical evaluations were made between the uncorrected SPT-N blow count and the corrected SPT-N(N_{60}) blow count and shear wave velocity (V_s). Based on statistical evaluations, empirical equations were developed to estimate V_s from the SPT-N blow count and the SPT-N(N_{60}) blow count, and the predictive ability of these equations was compared with that of equations proposed in previous studies.

2. Previous Studies

The soil amplification effect in settlement areas close to active fault zones is an extremely important feature in terms of soil–structure interactions. Engineers design earthquake-resistant structures by considering the dynamic behavior of the soil. Therefore, the determination of the shear wave velocity (V_s) of the soil has gained great importance. Over the years, many researchers have studied the relationship between the standard penetration resistance (SPT-N) of soil and geological age, and the soil type is often used by researchers to develop correlations between the shear wave velocity and the N value [21–26]. Additionally, Imai [22] reported that sandy soils showed a better correlation and higher velocities than cohesive soils.

Sykora and Stokoe [27] stated that the geological age and class of the soil did not determine the shear wave velocity effectively and that the important parameter was the SPT-N value. Iyisan [28] examined the correlations between SPT-N and V_s for all soils, sandy soils, and clayey soil types. The study was conducted in an earthquake-sensitive region in eastern Turkey. According to the results of the study, approximately similar Vs values were obtained for all soil types (except gravel soil). Hasancebi and Ulusay [29] produced empirical equations for all soils, sandy soils, and clayey soils, using 97 data pairs (V_s and SPT-N) in the Yenisehir district in the Marmara Region of Turkey. They also compared these empirical equations with previous studies. Ulugergerli and Uyanik [30] investigated 327 test sites in western Turkey, with predominantly clay–silt–sand–gravel deposits. Exponential curve fitting was used to identify the upper and lower bounds for the correlation between seismic velocities with SPT-N and the relative density.

Hanumantharao and Ramana [31] measured shear wave velocity profiles in the field at more than 80 borehole locations, using the spectral analysis of surface waves (SASWs), in the Delhi residential area (India). The authors stated that the results presented in this study could be used in microzonation studies and site-specific ground response analyses in Delhi. Dikmen [32] carried out shear wave velocity and standard penetration test studies in a part of the Eskisehir settlement area in Turkey. As a result of these studies, empirical equations for SPT-N and V_s were obtained for all soils, sand, silt, and clay. To investigate the predictive capability, these correlation equations were compared with previously suggested equations. Maheswari et al. [1] investigated the development of empirical correlations between Vs and SPT-N for different categories of soil in Chennai city, characterized by complex variations in the soil conditions. The extensive shear wave velocity measurement was carried out using the multichannel analysis of surface waves (MASWs) technique at sites where the SPT-N values were available. In addition, correlations between the energy-corrected and -uncorrected shear wave velocity and SPT-N for all soils, sandy soils, and clayey soils were analyzed by the researchers. Akin et al. [33] examined the empirical correlations between the shear wave velocity and SPT blow counts, in order to characterize shear wave velocity profiles in Erbaa in northeast Turkey.

Mhaske and Choudhury [17] developed a correlation between the SPT-N value and the shear wave velocity (V_s) for various soil profiles in the city of Mumbai and compared it with other correlations available for different cities in India. In addition, a geospatial contour map of the shear wave velocity profile, with contour intervals of 25 and 50 m/s, was prepared for the city of Mumbai using geographic information systems (GISs). Chatterjee and Choudhury [2] proposed a modified advanced approach for the city of Kolkata (India), to obtain the shear wave velocity profile and a soil site classification using regression and sensitivity analyses. Using the 434 boreholes in this study, the main soil types in the city of Kolkata were found to be clay, silt, and silty sand. Esfehanizadeh et al. [3] investigated the SPT and shear wave velocity of soil in several coastal cities on the Caspian Sea. In this study, downhole tests were performed to calculate the shear wave velocity profile in all the study sites using the same borehole and, in some cases, drilling a new borehole. After that, the data were analyzed, to determine the correlation via a suitable statistical method. The results indicated that the obtained relationship is suitably compatible with the universal practical relationship presented for sandy soils, and is approximately at the upper limit of the relationship.

A new empirical formula that can be used to correlate the SPT-N and V_s values for the typical soil materials encountered in north Florida was suggested by Fatehnia et al. [4]. Soil classification information, the shear wave velocity (derived via the MASWs method), and SPT-N values were gathered from four geotechnical and geophysical investigations conducted in this region. Through the employment of the M5 model tree algorithm, the relationship between the V_s and SPT-N values was predicted using the collected dataset. The accuracy of the new proposed equation was determined through the measurement of the correlation coefficient. The proposed correlation was also compared with previously suggested formulas for V_s determination through the measurement of the root-mean-square error of each formula. Kirar et al. [5] examined the development of a reliable correlation between Vs, measured via a multi-channel analysis of surface wave tests, and N, measured via SPT at various sites in the Roorkee region. These tests were carried out at ten different sites in Roorkee (within a radius of 30 km). Additionally, based on statistical assessments, an empirical correlation between V_s and N was developed for all types of soils, sand, and clay. Empirical equations for the Vs and SPT-N values in different soil types in different regions of the world were examined by Sil and Haloi [6]. These equations were selected separately, and statistical regression analyses were carried out to develop new common correlations for each type of soil. The newly developed equations had best-fit curves with very high R^2 values, along with minimum variance.

Ataee et al. [7] investigated the correlation between the shear wave velocity and standard penetration test blow counts in all soil types, gravelly soil, sandy soil, and clayey soil for the city of Mashhad in the northeastern region of Iran. The V_S data used were measured via the downhole method in 88 boreholes. The obtained results showed that the *N*-value played a critical role in the estimation of V_S, and the soil type was less effective in this regard. There was a relative similarity between the regression equations obtained in this study and those previously published. Shukla and Solanki [8] investigated generalized correlations between the shear wave velocity and SPT-N values for all soil types at a generalized depth, using the concept of regression. Soil profiles taken as input for analysis were collected from 245 boreholes in the Madhya Pradesh region (India). The researchers stated that multiple linear perceptron and generalized regression neural network models using MATLAB coding gave better results than linear regression analysis, when applied to site-specific ground response analysis.

3. Geology and Seismotectonics of the Study Area

The Canakkale settlement area is located in clastic formations and alluvial deposits deposited during the Middle Miocene–Pliocene. The clastic formations are defined as the "Canakkale Group" [34]. The Canakkale Group consists of four litho-stratigraphic units. However, the study area consists of the Gazhanedere and Alcitepe Formations (Figure 2).

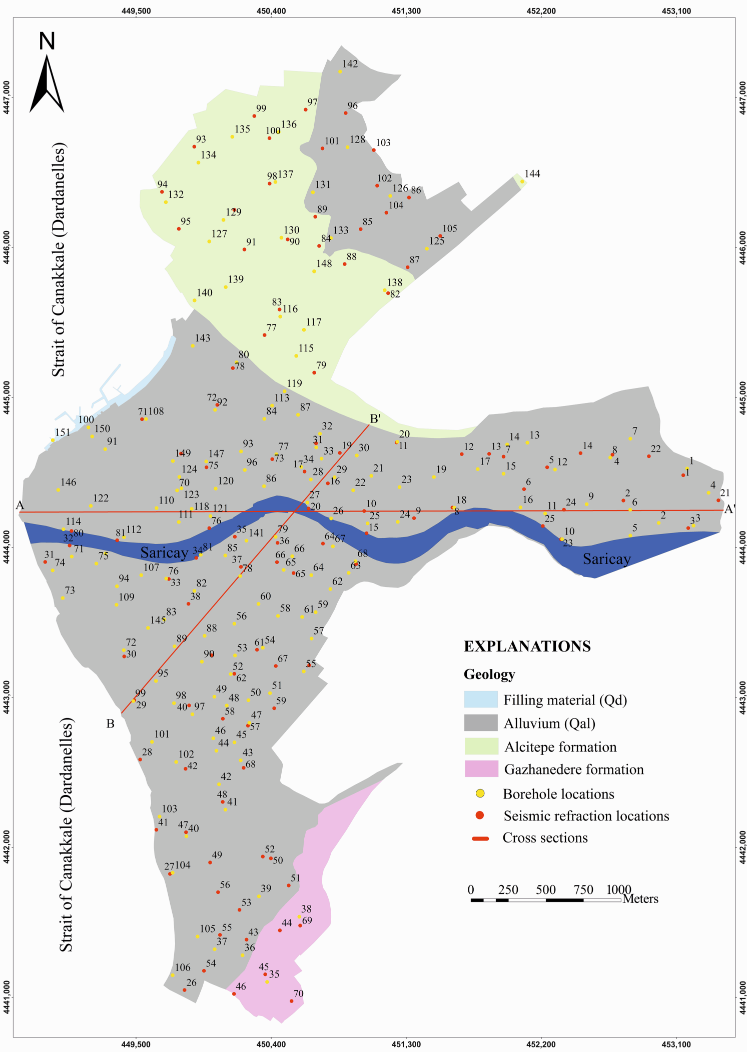

Figure 2. Geological map of the study area.

The Gazhanedere Formation is located in the southeast of the study area. It consists of sandstones and conglomerates belonging to longitudinal and transverse bar deposits, and reddish-grey mudstones forming floodplain deposits [35]. The Alcitepe Formation is seen in the north of the study area. It generally consists of sandstone, mudstone, sandy and clayey limestone, and marl [36].

Approximately two-thirds of the Canakkale residential area is constructed on soft Quaternary alluvium deposits carried by the Saricay stream. The Saricay stream flows from east to west in a perpendicular direction towards the Canakkale Strait (Dardanelles) and divides the city into two regions. Cross-section lines showing the lithological properties of the investigation area are given in Figure 3a,b.

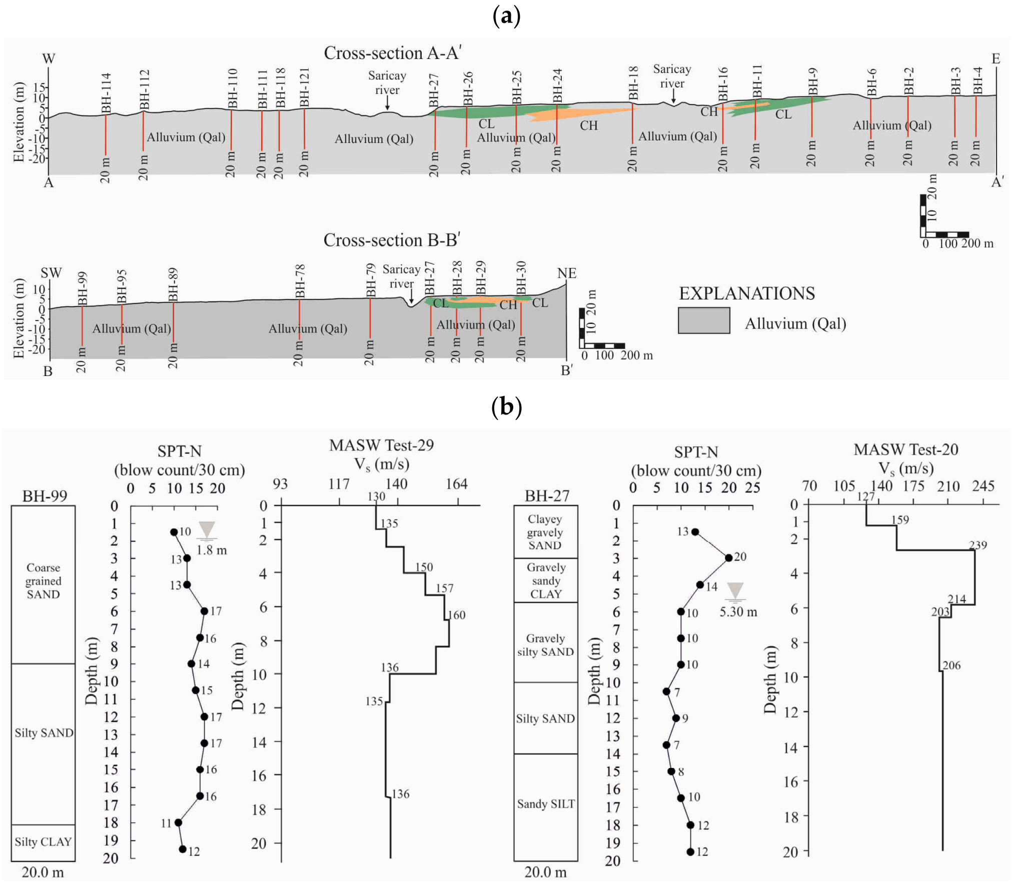

Figure 3. (**a**) Geological cross-sections, and (**b**) selected engineering logs illustrating the lithology, SPT-N values and V_s measured via MASWs tests in the study area.

There are fault zones in Turkey that have triggered many destructive earthquakes, past and present. The most important fault zone in Turkey is the North Anatolian Fault Zone (NAFZ). The NAFZ is a right-lateral strike-slip fault, with a total length of approximately 1600 km [37]. Canakkale Province is located between the central branch of the NAFZ, known as the Saros–Gazikoy Fault located at the westernmost end of the NAFZ, and the southern branch of the NAFZ, also known as the Yenice–Gonen Fault, located on the Biga Peninsula (Figure 4).

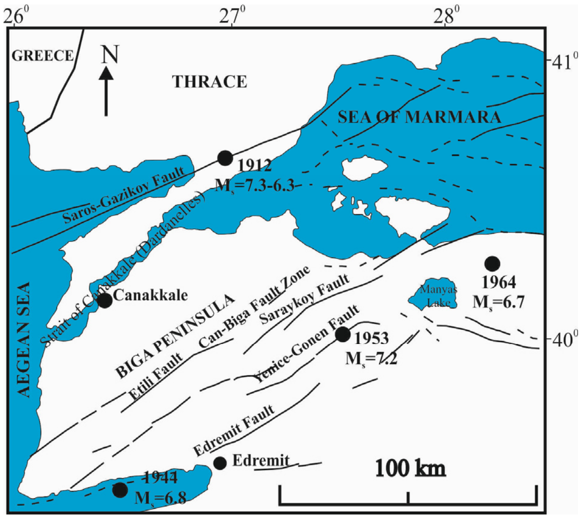

Figure 4. Active tectonic map of the Biga Peninsula [38].

In the middle of these two branches, the fault zone known as the middle branch of the NAFZ is located, and it passes through the Kapidag Peninsula, Can, and Bayramic districts. The Saros–Gazikoy Fault, Etili Fault, Can–Biga Fault Zone, Sarikoy Fault, and Yenice–Gonen Fault are located within the provincial borders of Canakkale. Tunusluoglu and Karaca [39] stated that the closest fault to the Canakkale settlement area is the Saroz–Gazikoy fault, and the earthquake magnitude it can produce may reach $M_w = 7.5$, with the highest horizontal ground acceleration value of 319 gal (0.325 g). Based on the Earthquake Hazard Map of Turkey, Interactive Web Application [15], the peak horizontal ground acceleration value identified for the Canakkale settlement area is 0.305 g (repetition period of 475 years).

4. Geotechnical and Geophysical Evaluations

4.1. Field Studies

Within the scope of microzonation studies in the Canakkale settlement area, 151 geotechnical boreholes with a total depth of 3000 m were drilled, in order to determine the engineering properties of the soil (Figure 2). During the geotechnical borehole studies, disturbed and undisturbed soil samples were taken for laboratory testing, and static groundwater level measurements were performed [20]. The SPT test [40] was performed every 1.5 m. The depth of the groundwater level in alluvial units varied between 0.6 m and 9.9 m. However, the depth of the groundwater level in the city center was generally around 2.0 m. The Alcitepe and Gazhanedere Formations within the study area were defined as rock mass. The borehole and seismic refraction locations in these formations were excluded from the study area. Quaternary alluvial deposits are observed in the center, east, north, and south parts of the Canakkale settlement area. The alluvial deposit in the north was excluded from the study area, due to the presence of thick pebbly levels. The liquefaction severity index (L_s) was found by Tunusluoglu and Karaca [39] to be moderate for this alluvial deposit.

The alluvial deposits in the study area were generally defined as sandy soil (SP, SW, SC, and SM) and, rarely, clayey bands were observed. In some parts of the alluvial deposits, the SPT-N blow count was determined as 10 between the surface and a depth of 5 m, but the SPT-N blow count increased at deeper depths, and the alluvium was defined as loose to partially dense. The average SPT-N blow count was between 10 and 25 at depths from 10 to 20 m in the borehole (Figure 3b).

4.2. Laboratory Studies

In order to determine the physical properties of the alluvial deposits in the central, eastern, and southern regions of the Canakkale settlement area, soil mechanics tests were performed on disturbed samples taken from the boreholes (Table 1). Laboratory studies were performed, following the methods defined by the ASTM [17]. The upper levels (1.5–3.0 m) in some locations in the alluvial deposits consist of clayey alluvial soil, while the lower levels consist of coarse-grained sandy alluvial soil. The unit weight values of the clayey soil in the alluvial deposit were determined based on undisturbed samples taken from 1.5 to 3.0 m depths. The fine-grained alluvial soil in the study area consists of, on average, 1.4% gravel-, 21% sand-, and 77.6% silt- and clay-sized soil. The coarse-grained alluvial soils in the study area consist of sand-sized soil and generally constitute alluvial soil below a 3.0 m depth. The coarse-grained alluvial soil consists of, on average, 3% gravel-, 85.3% sand-, and 11.7% silt- and clay-sized soil (Table 1). According to the grain-size analysis, 83.6% of the samples are coarse-grained soils, and 16.4% of the samples are fine-grained soils (Table 1).

Table 1. Geotechnical properties of the Quaternary alluvium in the center, eastern, and southern sections of the city of Canakkale.

Properties	**Fine-Grained Soils (ML, CL, MH, and CH)**						**Coarse-Grained Soils (SC, SM, SP, and SW)**					
	Sample Count	**Min**	**Max**	**Mean**	**SD**	**SE**	**Sample Count**	**Min**	**Max**	**Mean**	**SD**	**SE**
Nat. water cont., w_n (%)	155	9.6	67.6	28.3	8.93	0.72	-	-	-	-	-	-
Unit weight γ_n, (kN/m^3)	27	18.13	21.41	18.38	0.61	0.12	-	-	-	-	-	-
Liquid limit, LL (%)	149	24	73.5	47.8	11.84	0.97	35	23.5	56.5	32.3	6.16	1.04
Plastic limit, PL (%)	149	17	29.5	23.4	4.46	0.37	35	14.6	29.3	17.7	3.34	0.56
Plasticity index, PI (%)	149	7	44	22.4	8.31	0.68	35	8.9	27.2	14.7	3.90	0.66
#4 sieve (%)	156	0	5.3	1.4	1.44	11.09	798	0	43.6	3	5.93	0.21
#200 sieve (%)	156	51.2	96.4	77.6	11.09	0.89	798	0.2	49.5	11.7	9.38	0.33

4.3. Geoseismic Investigations

Within the scope of the geophysical studies in the microzonation study [20], 105 seismic refraction measurements with different profile lengths were taken in the Canakkale settlement area (Figure 2). The MASWs studies were carried out at the same locations as the seismic refraction profiles. The seismic recording data were filtered, corrected, and evaluated via inverse analysis, using a computer program, and the V_s velocities varying with depth were determined (Figure 3b). Within the scope of this study, the seismic refraction profiles at almost the same locations as the boreholes were examined, and the shear wave velocity (V_s) data, which were compatible with the SPT blow count, were used for the proposed empirical correlation.

5. Materials and Methods

5.1. Empirical Calculation of the Shear Wave Velocity (V_s)

For the shear wave velocity (V_s) determined using the SPT-N blow count, many studies were carried out for different soils, and empirical approaches based on the SPT-N blow count have been produced [1–8,17,21–33,41–56]. These empirical approaches consist of equations using the uncorrected SPT-N blow counts, as well as equations using the energy-corrected SPT-N(N_{60}) blow counts. While previous studies generally examined the relationships between the V_s–SPT-N measurements for all soils, in this study, only the relationship between the V_s–SPT-N measurements for sandy soil was investigated. In addition, statistical criteria, such as the mean square error (MSE), root-mean-square error (RMSE), mean absolute percent error (MAPE) and mean absolute error (MAE), were used to compare the estimation performance of the regression equations developed for the uncorrected SPT-N blow count and the corrected SPT-N (N_{60}) blow count.

The boundaries of the study area were determined as alluvial deposits in the central, eastern, and southern regions of the Canakkale settlement area. A total of 125 geotechnical borehole studies and 73 seismic refraction measurements with different profile lengths were carried out in this area (Figure 2). As geotechnical and geophysical studies carried out in the scope of the microzonation studies in the Canakkale settlement area were performed at different times, and by different teams, as well as due to the negative physical conditions in the city of Canakkale, full compatibility could not be achieved for the locations of boreholes and seismic refraction measurement points. Therefore, in this study, borehole locations and seismic refraction measurement points that are close to each other were compared. Furthermore, locations showing an inconsistency between the V_s velocity and SPT-N blow count were not included in this study. Within the scope of this study, empirical correlations between the uncorrected SPT-N value and energy-corrected SPT-N(N_{60}) value, and V_s taken from 50 seismic refraction measurement points and 50 geotechnical borehole locations in Quaternary alluvial deposits in the center, east, and south of the Canakkale settlement area were examined (Figure 5).

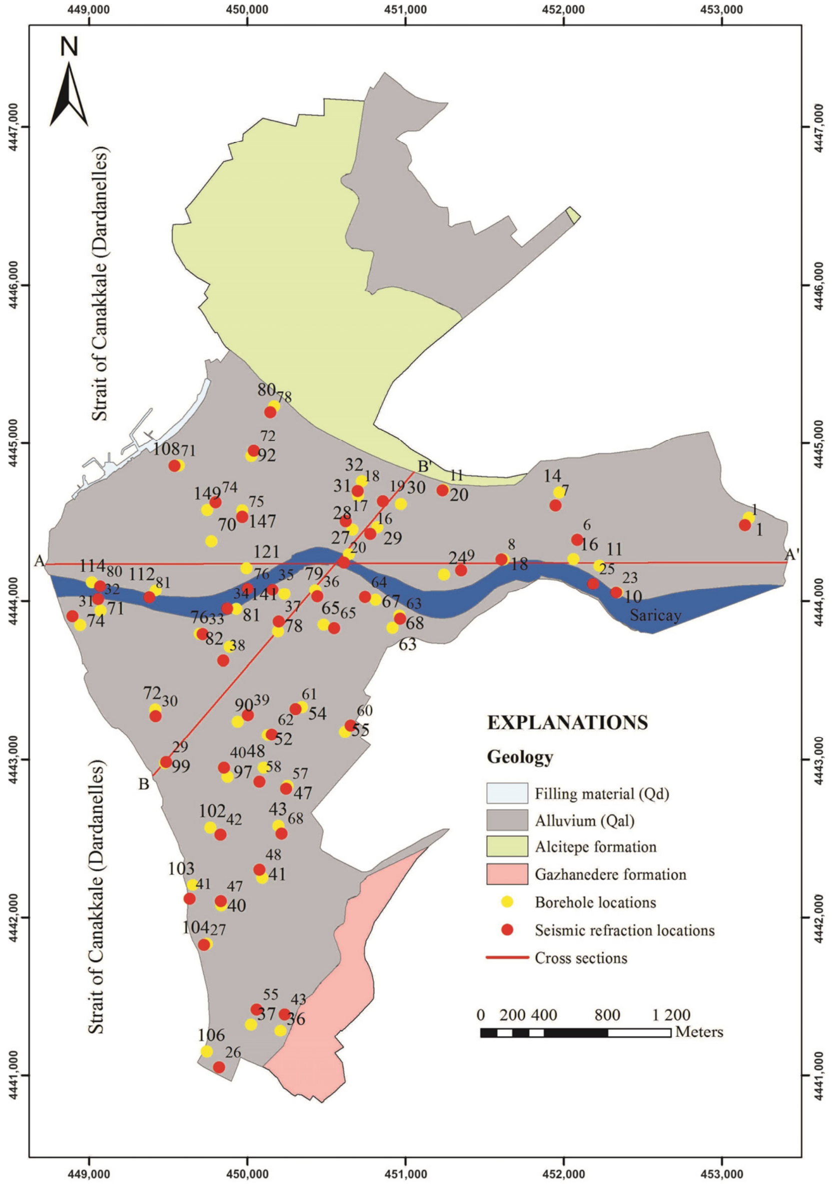

Figure 5. The borehole and seismic refraction locations used in the empirical correlations.

5.2. Suggested Empirical Correlation for V_s-SPT(N)

According to the grain-size analysis data (Table 1) for the samples taken from the study area, 83.6% of the samples are coarse-grained and, on average, 85.3% of the coarse-grained alluvial soil is sandy soil. Considering that the Canakkale residential area is predominantly located on sandy alluvial soil, the relationship between the V_s value of sandy alluvial soil and SPT-N was investigated in this study (Table 2). When creating correlations, a simple regression analysis was performed using the existing data. The equation and correlation coefficient (r) obtained between the V_s (m/s) and SPT-N values for the sandy alluvial soil in the study area are as follows:

$$V_s = 59N^{0.42}\left(\mathrm{R}^2 = 0.451 - \mathrm{r} = 0.67\right) \text{ sandy alluvial soil} \tag{2}$$

Table 2. Some empirical correlations based on V_s vs. SPT-N and V_s vs. SPT-N_{60}.

Author(s)	**V_s (m/s) vs. SPT-N**	**V_s (m/s) vs. SPT-N_{60}**
	Sandy Soils	
Shibata [43]	$V_s = 32N^{0.5}$	-
Ohta et al. [44]	$V_s = 87N^{0.36}$	-
Ohsaki and Iwasaki [21]	$V_s = 59.4N^{0.47}$	-
Imai [22]	$V_s = 80.6N^{0.331}$	-
Ohta and Goto [23]	$V_s = 88N^{0.34}$	-
Seed et al. [47]	$V_s = 56.4N^{0.5}$	-
Sykora and Stokoe [27]	$V_s = 100.5N^{0.29}$	-
Fumal and Tinsley [48]	$V_s = 152 + 5.1N^{0.27}$	-
Okamoto et al. [50]	$V_s = 125N0.3$	-
Lee [51]	$V_s = 57N^{0.49}$	-
Pitilakis et al. [25]	$V_s = 162N^{0.17}$	-
Raptakis et al. [26]	$V_s = 100N^{0.24}$	-
Pitilakis et al. [54]	-	$V_s = 145(N_{60})^{0.178}$
Hasancebi and Ulusay [29]	$V_s = 90.82N^{0.319}$	$V_s = 131(N_{60})^{0.205}$
Hanumantharao and Ramana [31]	$V_s = 79N^{0.434}$	-
Dikmen [32]	$V_s = 73N^{0.33}$	-
Maheswari et al. [1]	$V_s = 100.53N^{0.265}$	$V_S = 96.29(N_{60})^{0.266}$
Akin et al. [33]	$V_s = 38.55N^{0.176}z^{0.481}$	-
Chatterjee and Choudhury [2]	$V_s = 54.82N^{0.52559}$	-
Esfehanizadeh et al. [3]	$V_s = 107.2N^{0.34}$	-
Kirar et al. [5]	$V_s = 100.3N^{0.338}$	-
Sil and Haloi [6]	$V_s = 79.217N^{0.3699}$	-
Ataee et al. [7]	$V_s = 135.52N^{0.415}$	$V_s = 69.18(N_{60})^{0.506}$

The correlation for sandy alluvial soils in this study is plotted in Figure 6.

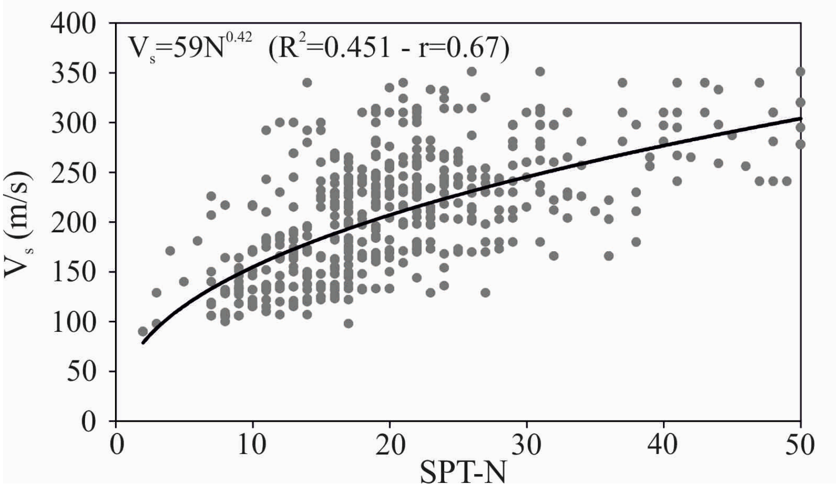

Figure 6. Correlations between V_s and SPT-N for sandy alluvial soil.

Equation (2) was also compared with the correlations suggested for sandy soils in previous studies (Figure 7).

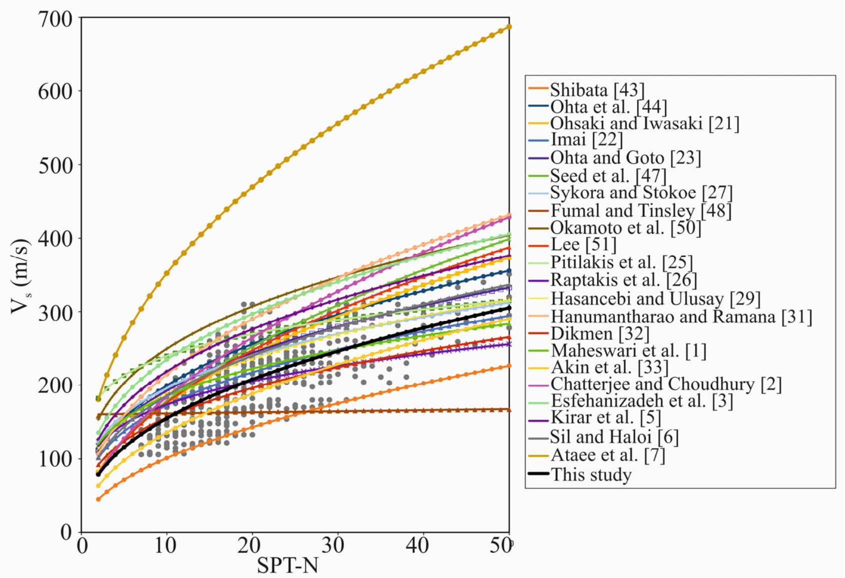

Figure 7. Comparison of correlations suggested in this study and previous studies for V_s and SPT-N for sandy soil [1–3,5–7,21–23,25–27,29,31–33,43,44,47,48,50,51].

5.3. Suggested Empirical Correlation for V_s–SPT-N(N_{60})

In this study, in addition to the correlation between the V_s and SPT-N being examined, the correlation between the V_s and energy-corrected SPT-N(N_{60}) values was investigated, and an equation was established for sandy soils. During SPT tests, the SPT-N blow counts are corrected via impact energy corrections. A donut-type hammer is used in Turkey, and the hammer is dropped through the application of two cycles to the rope. After the 60% energy correction of the standard rod energy, the blow counts are shown with the symbol N_{60}, and the energy-corrected SPT-N blow counts are determined by the following equation:

$$N_{60} = N\frac{E_r}{60} \tag{3}$$

where N is the blow count obtained directly from the SPT experiment, and the energy ratio (E_r) is 45.

The equation and correlation coefficient (r) for the sandy alluvial soil in the study area, obtained as a result of regression analysis between the V_s (m/s) and N_{60} values, are as follows:

$$V_s = 83{N_{60}}^{0.343}\left(\mathrm{R}^2 = 0.303 - \mathrm{r} = 0.55\right) \text{ sandy alluvial soil} \tag{4}$$

The regression analysis graph between V_s and N_{60} is given in Figure 8.

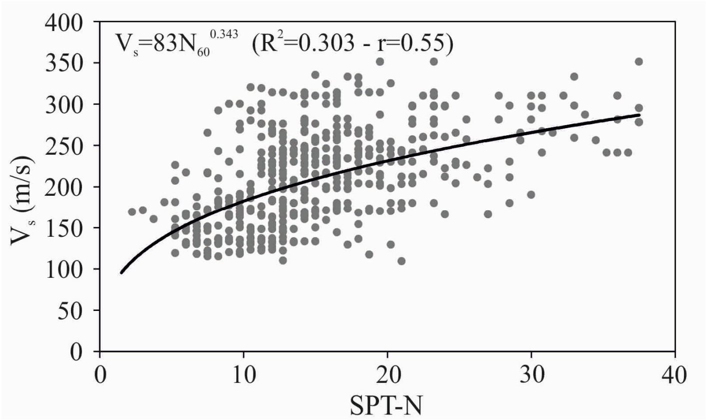

Figure 8. Correlations between V_s and SPT-N_{60} for sandy alluvial soil.

6. Results and Discussion

The measured V_s values and the estimated V_s values according to Equation (2) are compared in Figure 9. The values obtained as a result of the comparison are distributed between the 1:0.5 and 1:2 slopes, and the V_s values between 150 and 250 m/s are concentrated in the 1:1 line frame.

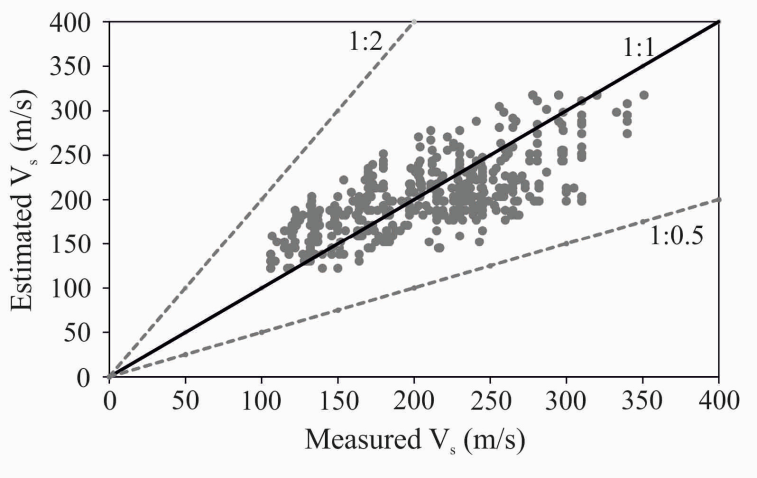

Figure 9. Graph of the measured, versus estimated, shear wave velocity for sandy alluvial soil.

Based on the comparison for sandy soils, the resulting equations obtained by Imai [22] and Dikmen [32] gave similar results to the V_s values obtained in this study at certain blow-count intervals (Figure 10).

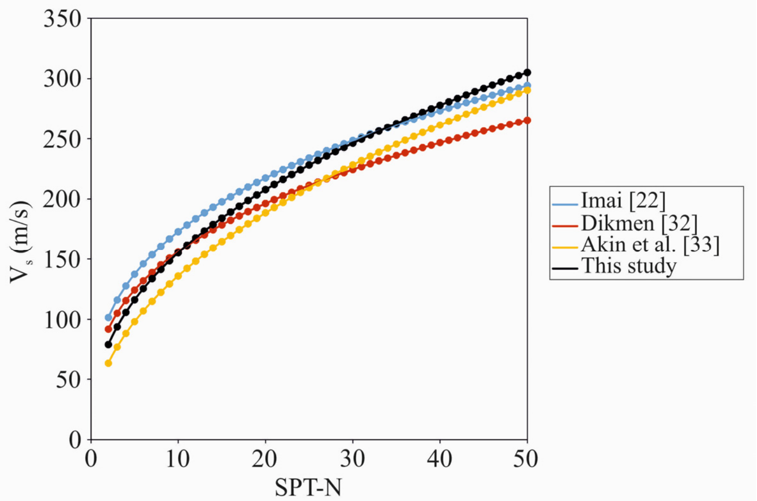

Figure 10. Comparison of previous studies consistent with this study for V_s and SPT-N [22,32,33].

In the equation proposed by Imai [22], V_s values similar to those in this study were obtained for the number of impacts $30 \leq N \leq 40$, while higher V_s values were obtained for $N < 30$ than the V_s values obtained from this study, and lower V_s values were obtained for $40 < N$. However, in the equation proposed by Dikmen [32], V_s values similar to those in this study were obtained for $N \leq 15$, while lower V_s values were obtained for $15 < N$ than the V_s values obtained in this study (Figure 10). Moreover, when the equation proposed by Akin et al. [33] was compared with the equation obtained in this study, the equations gave close results, and the data distribution was similar (Figure 10). These differences between the correlation results could be due to the different soil conditions in the study areas, the number of data points used, the SPT applications, and the different V_S measurement methods used in the studies.

In addition to the comparison of previous studies consistent with this study for sandy soil given in Figure 10, the scale error percentage (Equation (5)) and cumulative frequency graphs are also given in Figure 11.

$$\text{Scaled percent error} = \left[\frac{V_{sc} - V_{sm}}{V_{sm}}\right] \times 100 \tag{5}$$

where V_{sc} and V_{sm} are the predicted and measured shear wave velocities, respectively.

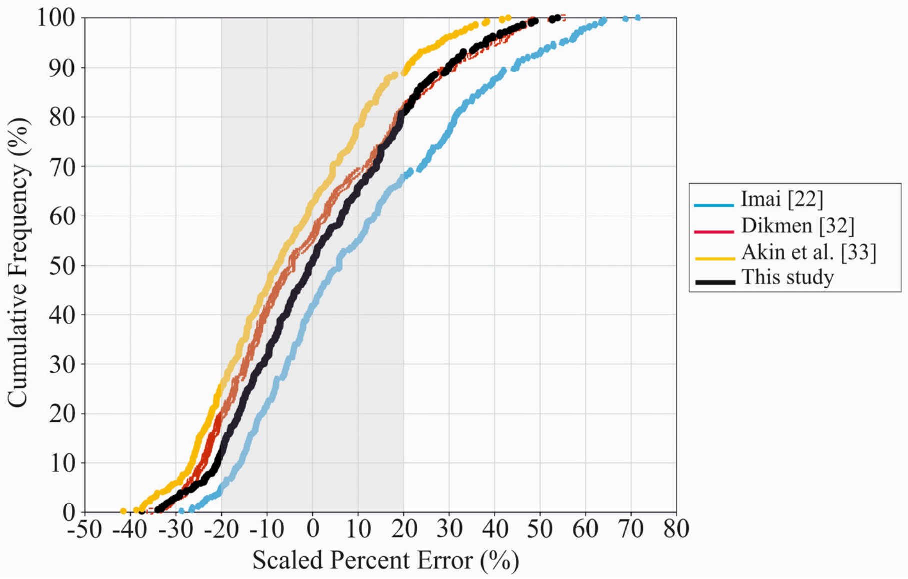

Figure 11. Scaled percentage error of the V_s values estimated for sandy soils [22,32,33].

As can be seen in Figure 11, approximately 70% of the V_s values predicted via Equation (2) are within 20% of the scaled percent error. This indicates a slightly higher prediction than 67% obtained via Equation (2).

When the correlation coefficient between V_s and N_{60} is compared with Equation (2), the correlation coefficient obtained with the uncorrected SPT-N had a slightly better value than the energy-corrected correlation coefficient. The measured V_s values and the V_s values estimated according to Equation (4) are compared in Figure 12. Based on the comparison, the data were distributed between a 1:05 and 1:2 slope and the V_s values between 175 and 250 m/s were concentrated along the 1:1 line.

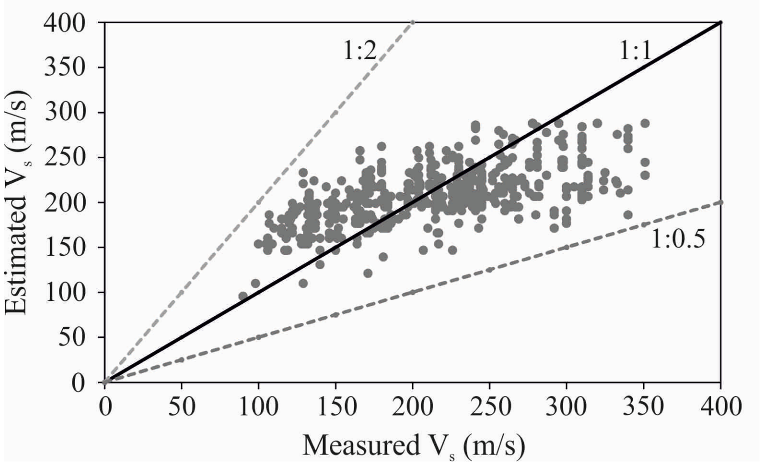

Figure 12. Graph of the estimated, versus measured, shear wave velocity, using SPT-N_{60}.

The equation between V_s and N_{60} given in Equation (4) was compared with the regression correlations for sandy soils in Figure 13. Based on the comparison, the equations obtained by Pitilakis et al. [54] and Hasancebi and Ulusay [29] provided similar results to the V_s values obtained in this study at certain blow-count intervals. The V_s values obtained with the equation proposed by Pitilakis et al. [54] and Hasancebi and Ulusay [29] for the number of pulses $N_{60} < 27$ were larger than the V_s values obtained in this study. For $27 \leq N_{60} \leq 32$, the equations by Pitilakis et al. [54] and Hasancebi and Ulusay [29] yielded similar results to the V_s values obtained in this study. Slightly lower V_s values were obtained with the equations suggested by Pitilakis et al. [54] and Hasancebi and Ulusay [29] for $32 < N_{60}$. Furthermore, the equations obtained by Maheswari et al. [1] and Ataee et al. [7] provided similar results to the V_s values obtained in this study for SPT-N blow counts less than 10 (Figure 13).

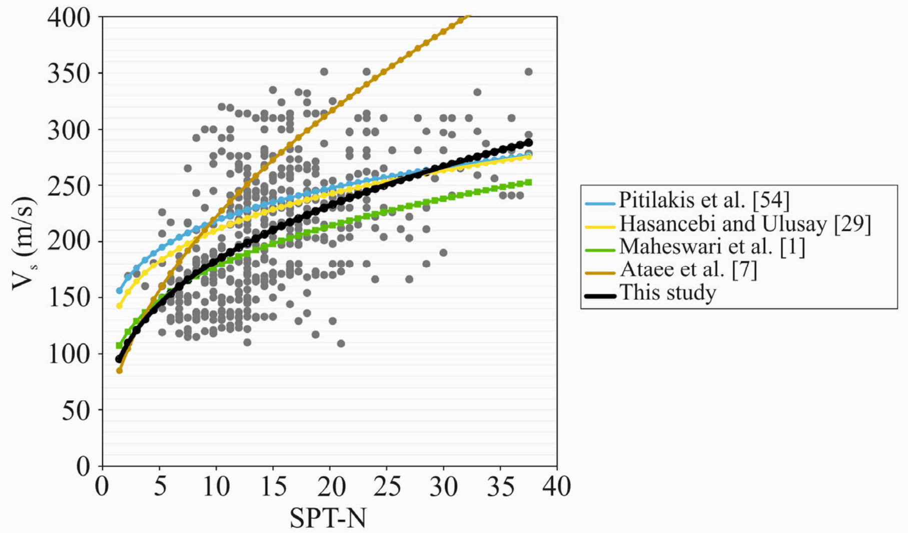

Figure 13. Comparison of the correlations suggested in this study and those from previous studies for V_s and SPT-N_{60} [1,7,29,54].

The error criteria given in Table 3 were used to measure the estimation performance of the empirical correlations proposed in this study. The error criteria used were the mean square error (MSE), root-mean-square error (RMSE), mean absolute percent error (MAPE), and mean absolute error (MAE).

Table 3. The error criteria used in the performance measurement.

Error Criteria	Error Formula
MSE	$MSE = \frac{\sum_{i=1}^{n}(m_i - p_i)}{n}$
RMSE	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(m_i - p_i)^2}{n}}$
MAPE	$MAPE = \frac{\sum_{i=1}^{n}\left\lvert\frac{m_i - p_i}{m_i}\right\rvert}{n} \times 100$
MAE	$MAE = \frac{\sum_{i=1}^{n}\lvert m_i - p_i\rvert}{n}$

Where m_i is the measured value, p_i is the predicted value, $\overline{m}$ is the mean of the measured values, and n is the number of data in the database.

The low results for the error criteria MSE, RMSE, MAPE, and MAE show a high performance, with the error results inversely proportional to the performance [57] (Table 4).

MAPE is one of the most popular measures used to predict accuracy [58]. It measures the average magnitude of error produced by a model, or how far off predictions are on average. A MAPE value of 16% means that the average absolute percentage difference between the predictions and the actual values is 16% for the uncorrected V_S–SPT-N correlation. The amount of deviation for the corrected V_s–SPT-N(N_{60}) correlation was found to be 20%.

Table 4. Evaluation of the uncorrected V_S–SPT-N and corrected Vs–SPT-N(N_{60}) correlations with the error criteria for the power model.

	Uncorrected V_s–SPT-N					Corrected V_s–SPT-N(N_{60})				
Model	**r**	**MSE**	**RMSE**	**MAPE**	**MAE**	**r**	**MSE**	**RMSE**	**MAPE**	**MAE**
Power	0.67	1516	39	16	32	0.55	2288	48	20	39

7. Conclusions

In this study, the aim was to indirectly estimate V_s by establishing a relationship between the number of SPT-N blow counts and shear wave velocity (V_s) data obtained as a result of microzonation studies carried out in the Canakkale residential area located in northwest Turkey. The results obtained from this study and the regression analyses can be summarized as follows:

(a) A simple regression equation was produced between the SPT-N and shear wave velocity (V_s) data for sandy soils in the Canakkale residential area.
(b) The regression equation developed in this study was similar to some previous studies and provided a good estimation performance.
(c) Comparing the equations produced using the SPT-N data and energy-corrected SPT-N(N_{60}) data with other previous studies, the equation produced with the SPT-N showed a better estimation performance for V_s.
(d) The empirical equation produced in this study will be useful in estimating the shear wave velocity (V_s) and the shear modulus required for practical dynamic analysis in cases where seismic tests cannot be performed, or are limited in number.
(e) The data were analyzed via nonlinear regression analysis, using a power model. Additionally, the amount of deviation from accuracy was determined using error criteria. The correlation coefficient (r) and MAPE values for the power model showed a good agreement between the uncorrected Vs–SPT-N and corrected Vs–SPT-N(N_{60}) correlations.
(f) The predictive ability of the proposed equation between SPT-N and V_s can be further improved through the use of data obtained via in-hole seismic methods, as well as through an increase in the number of seismic refraction profiles in future studies.
(g) The differences between the equations proposed in previous studies and the equations proposed in this study are due to the soil properties of the investigated area, as well as the depth, groundwater level, number of data processed, and seismic measurement techniques used.
(h) This study was carried out on sandy soils in the Canakkale residental area. Researchers who hope to benefit from this study can use the suggested equations if they are working with similar soil properties, depths, SPT-N blow counts, and V_s values. The equations will allow them to approximate the V_s values in their field of study.
(i) The careful use of the produced equation, and checking with the shear wave velocity values measured at certain locations will increase the accuracy of dynamic analyses.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this study are microzonation project data financed by Canakkale Municipality. For this reason, data cannot be shared without the permission of Canakkale Municipality. According to the agreement made with Canakkale Municipality, the authors of the microzonation report have the right to use the data.

Acknowledgments: The author would like to express their gratitude to the municipality of Canakkale for information, the microzonation report, and the logs for the geotechnical boreholes.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Maheswari, R.U.; Boominathan, A.; Dodagoudar, G.R. Use of Surface Waves in Statistical Correlations of Shear Wave Velocity and Penetration Resistance of Chennai Soils. *Geotech. Geol. Eng.* **2010**, *28*, 119–137. [CrossRef]
2. Chatterjee, K.; Choudhury, D. Variations in shear wave velocity and soil site class in Kolkata city using regression and sensitivity analysis. *Nat. Hazards* **2013**, *69*, 2057–2082. [CrossRef]
3. Esfehanizadeh, M.; Nabizadeh, F.; Yazarloo, R. Correlation between standard penetration (NSPT) and shear wave velocity (VS) for young coastal sands of the Caspian Sea. *Arab. J. Geosci.* **2015**, *8*, 7333–7341. [CrossRef]
4. Fatehnia, M.; Hayden, M.; Landschoot, M. Correlation between Shear Wave Velocity and SPT-N Values for North Florida Soils. *Electron. J. Geotech. Eng.* **2015**, *20*, 12421–12430.
5. Kirar, B.; Maheshwari, B.K.; Muley, P. Correlation between Shear Wave Velocity (Vs) and SPT Resistance (N) for Roorkee Region. *Int. J. Geosynth. Ground Eng.* **2016**, *2*, 9. [CrossRef]
6. Sil, A.; Haloi, J. Empirical Correlations with Standard Penetration Test (SPT)-N for Estimating Shear Wave Velocity Applicable to Any Region. *Int. J. Geosynth. Ground Eng.* **2017**, *3*, 22. [CrossRef]
7. Ataee, O.; Moghaddas, N.H.; Lashkaripour, G.R. Estimating shear wave velocity of soil using standard penetration test (SPT) blow counts in Mashhad city. *J. Earth Syst. Sci.* **2019**, *128*, 66. [CrossRef]
8. Shukla, D.; Solanki, C.H. Estimated Empirical Correlations Between Shear Wave Velocity and SPT-N Value for Indore City Using NLR and ANN. *Indian Geotech. J.* **2020**, *50*, 784–800. [CrossRef]
9. Iyisan, R.; Ansal, A. Determination of Dynamic Soil Properties in Erzincan by In-Hole Seismic Measurements. In Proceedings of the 2nd National Earthquake Engineering Conference, Proceedings Book, Istanbul, Turkey, 13 March 1993; pp. s372–s379. (In Turkish)
10. Kramer, S.L. *Geotechnical Earthquake Engineering*; Prentice Hall: Upper Saddle River, NJ, USA, 1996; 653p.
11. Andrus, R.D.; Stokoe, K.H. Liquefaction resistance based on shear wave velocity in evaluation of liquefaction resistance of soils. In *National Center for Earthquake Engineering Research (NCEER) Workshop*; Youd, T.L., Idriss, I.M., Eds.; NCEER: Salt Lake, UT, USA, 1997; pp. 89–128.
12. Seed, R.B.; Cetin, K.O.; Moss, R.E.S.; Kammerer, A.M.; Wu, J.; Pestana, J.M.; Riemer, M.F.; Sancio, R.B.; Bray, J.D.; Kayen, R.E.; et al. Recent advances in soil liquefaction engineering: A unified and consistent framework. In Proceedings of the 26th Annual ASCE Los Angeles Geotechnical Spring Seminar, Long Beach, CA, USA, 30 April 2003; ASCE: Reston, VA, USA, 2003; p. 71.
13. Aydin, K. A Study on SPT-V_s Correlation on Ankara Subway Routes. Master's Thesis, Institute of Natural Sciences, Gazi University, Ankara, Türkiye, 2010; p. 120. (In Turkish)
14. Porcino, D.D.; Tomasello, G. Shear wave velocity-based evaluation of liquefaction resistance for calcareous sands of different origin. *Soil Dyn. Earthq. Eng.* **2019**, *122*, 235–247. [CrossRef]
15. Rahimia, S.; Wooda, C.M.; Wotherspoonb, L.M. Influence of soil aging on SPT-Vs correlation and seismic site classification. *Eng. Geo.* **2020**, *272*, 105653. [CrossRef]
16. Papadopoulou, A.I.; Tika, T.M. Laboratory-Based Correlation between Liquefaction Resistance and Shear Wave Velocity of Sand with Fines. *Geotechnics* **2021**, *1*, 219–242. [CrossRef]
17. Mhaske, S.Y.; Choudhury, D. Geospatial contour mapping of shear wave velocity for Mumbai city Geospatial contour mapping of shear wave velocity for Mumbai city. *Nat. Hazards* **2011**, *59*, 317–327. [CrossRef]
18. AFAD (Ministry of Interior Disaster and Emergency Management Presidency). The Earthquake Hazard Map of Turkey, Interactive Web Applications. 2018. Available online: https://tdth.afad.gov.tr/TDTH/main.xhtml (accessed on 11 May 2023).
19. Pitilakis, K.; Anastasiadis, A.; Kakderi, K.; Manakou, M.; Manou, D.; Alexoudi, M.; Fotopoulou, S.; Argyroudis, S.; Senetakis, K. Development of comprehensive earthquake loss scenarios for a Greek and a Turkish city: Seismic hazard, geotechnical and lifeline aspects. *Earthq. Struct.* **2011**, *2*, 207–232. [CrossRef]
20. Buyuksarac, A.; Tunusluoglu, M.C.; Bekler, T.; Yalciner, C.C.; Karaca, O.; Ekinci, Y.L.; Demirci, A.; Dinc, S.O. *Geological and Geotechnical Investigation Project of Canakkale Settlement Area Prepared for Canakkale Municipality*; Canakkale Onsekiz Mart University: Çanakkale, Türkiye, 2013; p. 234. (In Turkish)
21. Ohsaki, Y.; Iwasaki, R. On dynamic shear moduli and Poisson's ratio of soil deposits. *Soils Found.* **1973**, *13*, 61–73. [CrossRef]
22. Imai, T. P and S wave velocities of the ground in Japan. In Proceedings of the International Conference on Soil Mechanics and Foundation Engineering, Tokyo, Japan, 10–15 July 1977; Volume 2, pp. 127–132.
23. Ohta, Y.; Goto, N. Empirical shear wave velocity equations in terms of characteristics soil indexes. *Earthq. Eng. Struct. Dyn.* **1978**, *6*, 167–187. [CrossRef]
24. Imai, T.; Tonouchi, K. Correlation of N-value with S-wave velocity and shear modulus. In Proceedings of the 2nd European Symposium of Penetration Testing, Amsterdam, The Netherlands, 24–27 May 1982; pp. 57–72.
25. Pitilakis, K.D.; Anastasiadis, A.; Raptakis, D. Field and laboratory determination of dynamic properties of natural soil deposits. In Proceedings of the World Conference on Earthquake Engineering, Rotherdam, The Netherlands, 19–24 July 1992; pp. 1275–1280.
26. Raptakis, D.G.; Anastasiadis, S.A.J.; Pitilakis, K.D.; Lontzetidis, K.S. Shear wave velocities and damping of Greek natural soils. In Proceedings of the 10th European Conference on Earthquake Engineering, Vienna, Austria, 28 August–2 September 1994; pp. 477–482.
27. Sykora, D.E.; Stokoe, K.H. Correlations of in-situ measurements in sands of shear wave velocity. *Soil Dyn. Earthq. Eng.* **1983**, *20*, 125–136.

28. Iyisan, R. Correlations between shear wave velocity and in-situ penetration test results. *Chamb. Civ. Eng. Turk.* **1996**, *7*, 1187–1199. (In Turkish)
29. Hasancebi, N.; Ulusay, R. Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments. *Bull. Eng. Geol. Environ.* **2007**, *66*, 203–213. [CrossRef]
30. Ulugergerli, U.E.; Uyanık, O. Statistical correlations between seismic wave velocities and SPT blow counts and the relative density of soils. *J. Test. Eval.* **2007**, *35*, 1–5. [CrossRef]
31. Hanumantharao, C.; Ramana, G.V. Dynamic soil properties for microzonation of Delhi, India. *J. Earth Syst. Sci.* **2008**, *117*, 719–730. [CrossRef]
32. Dikmen, U. Statistical correlations of shear wave velocity and penetration resistance for soils. *J. Geophys. Eng.* **2009**, *6*, 61–72. [CrossRef]
33. Akin, M.K.; Kramer, S.L.; Topal, T. Empirical correlations of shear wave velocity (V_s) and penetration resistance (SPT-N) for different soils in an earthquake-prone area (Erbaa-Turkey). *Eng. Geol.* **2011**, *119*, 1–17. [CrossRef]
34. Siyako, M. Thracian Basin Tertiary rock units. *Stratigr. Comm. Lithostratigr. Units Ser.-2* **2006**, 43–83. (In Turkish)
35. Atabey, E.; Ilgar, A.; Sakıtas, A. Middle-Upper Miocene stratigraphy of Canakkale, Canakkale, NW Turkey. *Bull. Min. Res. Exp.* **2004**, *128*, 79–97. (In Turkish)
36. Siyako, M.; Burkan, K.A.; Okay, A.I. Tertiary geology and hydrocarbon potential of the Biga and Gelibolu peninsulas. *Turk. Assoc. Pet. Geol.* **1989**, *1*, 183–199, (In Turkish with English Abstract).
37. Polonia, A.; Gasperini, L.; Amorosi, A.; Bonatti, E.; Bortoluzzi, G.; Cagatay, N.; Capotondi, L.; Cormier, M.H.; Gorur, N.; McHugh, C.; et al. Holocene slip rate of the North Anatolian Fault beneath the Sea of Marmara. *Earth Planet. Sci. Lett.* **2004**, *227*, 411–426. [CrossRef]
38. Gurbuz, C.; Aktar, M.; Eyidogan, H.; Cisternas, A.; Haessler, H.; Barka, A.; Ergin, M.; Turkelli, N.; Polat, O.; Ucer, S.B.; et al. The seismotectonics of the Marmara region (Turkey): Results from a microseismic experiment. *Tectonophysics* **2000**, *316*, 1–17. [CrossRef]
39. Tunusluoglu, M.C.; Karaca, O. Liquefaction severity mapping based on SPT data: A case study in Canakkale city (NW Turkey). *Environ. Earth Sci.* **2018**, *77*, 422. [CrossRef]
40. American Society for Testing Materials (ASTM). *Annual Book of ASTM, Standards-Soil and Rock, Building Stones*; ASTM: West Conshohocken, PA, USA, 2004; Section 4; Volume 04.08, p. 1369.
41. Ohba, S.; Toriumi, I. Dynamic response characteristics of Osaka Plain. In Proceedings of the Annual Meeting AIJ, Tokyo, Japan, 5–7 December 1970. (In Japanese)
42. Imai, T.; Yoshimura, Y. Elastic wave velocity and soil properties in soft soil. *Tsuchi-ToKiso* **1970**, *18*, 17–22. (In Japanese)
43. Shibata, T. Analysis of liquefaction of saturated sand during cyclic loading. *Disaster Prev. Res. Inst. Bull.* **1970**, *13*, 563–570.
44. Ohta, T.; Hara, A.; Niwa, M.; Sakano, T. Elastic shear modulus estimated from N-value. In Proceedings of the 7th Annual Convention of Japan Society of Soil Mechanics and Foundation Engineering, Tokyo, Japan, 10–15 July 1972; pp. 265–268.
45. Fujiwara, T. Estimation of ground movements in actual destructive earthquakes. In Proceedings of the Fourth European Symposium on Earthquake Engineering, London, UK, 5–7 September 1972; pp. 125–132.
46. Seed, H.B.; Idriss, I.M. *Evaluation of Liquefaction Potential Sand Deposits Based on Observation of Performance in Previous Earthquakes*; ASCE National Convention (MO): St. Louis, MO, USA, 1981; pp. 481–544.
47. Seed, H.B.; Idriss, I.M.; Arango, I. Evaluation of liquefaction potential using field performance data. *J. Geotech. Eng.* **1983**, *109*, 458–482. [CrossRef]
48. Fumal, T.E.; Tinsley, J.C. Mapping shear wave velocities of near surface geological materials. In Predicting areal limits of earthquake induced landsliding. In *Evaluation of Earthquake Hazards in the Los Angeles Region—An Earth Science Perspective*; Ziony, T.I., Ed.; USGS Paper; USGS: Reston, VA, USA, 1985; Volume 1360, pp. 127–150.
49. Jinan, Z. Correlation between seismic wave velocity and the number of blow of SPT and depth. *Sel. Pap. Chin. J. Geotech. Eng.* **1987**, *1*, 92–100.
50. Okamoto, T.; Kokusho, T.; Yoshida, Y.; Kusuonoki, K. Comparison of surface versus subsurface wave source for P-S logging in sand layer. In Proceedings of the 44th Annual Conference JSCE, Tokyo, Japan, October 1989; Volume 3, pp. 996–997. (In Japanese)
51. Lee, S.H. Regression models of shear wave velocities. *J. Chin. Inst. Eng.* **1990**, *13*, 519–532. [CrossRef]
52. Sisman, H. An Investigation on Relationships between Shear Wave Velocity, and SPT and Pressuremeter Test Results. Master's Thesis, Geophysical Engineering Department, Ankara University, Ankara, Turkey, 1995; 75p. (In Turkish)
53. Jafari, M.K.; Asghari, A.; Rahmani, I. Empirical correlation between shear wave velocity (V_s) and SPT-N value for south of Tehran soils. In Proceedings of the 4th International Conference on Sustainability in Civil Engineering, Tehran, Iran, 4–6 May 1997. (In Persian)
54. Pitilakis, K.; Raptakis, D.; Lontzetidis, K.T.; Vassilikou, T.; Jongmans, D. Geotechnical and geophysical description of Euro-Seistests, using field and laboratory tests, and moderate strong ground motions. *J. Earthq. Eng.* **1999**, *3*, 381–409. [CrossRef]
55. Kiku, H.; Yoshida, N.; Yasuda, S.; Irisawa, T.; Nakazawa, H.; Shimizu, Y.; Ansal, A.; Erkan, A. In-situ penetration tests and soil profiling in Adapazari, Turkey. In Proceedings of the ICSMGE, TC4 Satellite Conference on Lessons Learned from Recent Strong Earthquakes, Istanbul, Turkey, 1 August 2001; pp. 259–265.
56. Jafari, M.K.; Shafiee, A.; Razmkhah, A. Dynamic properties of fine grained soils in south of Tehran. *J. Seismol. Earthq. Eng.* **2002**, *4*, 25–35.

57. Wang, W.; Xu, Z. A Heuristic Training for Support Vector Regression. *Neurocomputing* **2004**, *61*, 259–275. [CrossRef]
58. Kim, S.; Kim, H. A new metric of absolute percentage error for intermittent demand forecasts. *Int. J. Forecast.* **2016**, *32*, 669–679. [CrossRef]