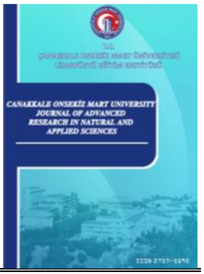
Çanakkale Onsekiz Mart University

Journal of Advanced Research in Natural and Applied Sciences

dergipark.org.tr/tr/pub/jarnas

Open Access



e-ISSN: 2757-5195 2024, Vol. 10, Issue 1, Pages: 161-174 doi.org/10.28979/jarnas.1393352

Correlating Measured SPT-N, Shear Wave Velocity and Liquid Limit Values in Melekli Region, Igdır (Türkiye)

Yusuf Guzel[1]

[1]Department of Civil Engineering, Faculty of Engineering, Necmettin Erbakan University, Konya, Türkiye

Article History
Received: 20 Nov 2023
Accepted: 31 Dec 2023
Published: 15 Mar 2024

Research Article

Abstract − Characterization of soil layers underneath or having interaction with structures is substantially critical for the overall stability of structures under static and dynamic conditions. The main objectives in characterizing soil are mainly to determine ultimate bearing capacity, settlement, and liquefaction potential. Additionally, the dynamic behavior of soil during seismic excitation, as well as its interaction with structures, should be determined. In these regards, Standard Penetration Test blow counts (SPT-N) and shear wave velocity (V_s) values of soils obtained directly through field tests are known to reflect the soil characteristics, strongly. Therefore, any correlation between these two soil parameters is always in utmost interest. This study assesses the correlation between V_s and SPT-N values measured in Melekli region, Igdır (Türkiye). Moreover, four existing correlations in the literature are presented. The best-fit curve for the measured data is shown to divert from the existing correlation curves, which are also significantly different from each other, for all soils, sand, and clay soils. This can be attributed to the uniqueness of correlation to the study site as geological conditions at one site differ extensively from another site. There seems to be valuable correlation between V_s and water content and liquid limit in the studied area.

Keywords − *Standard penetration test, blow count, shear wave velocity, liquid limit*, correlation

1. Introduction

Structures built whether on or below the ground surface are supported by the foundation soils. Determinations of foundation soil properties are necessary and vital so as to ensure the stability of structures [1]. By assessing the foundation soil features, the suitability of the soil for a project to be initiated is determined and necessary steps (foundation design, soil improvement etc), to ensure that the structures are supported safely, are projected [2].

The loads exposed by the structures cause increases in stresses within the soil bodies. As the soil layers deepen, the incremental stress caused by the structural loads diminishes. Soils layered through the deposits should be featured up to a depth at which the stress increment due to the structural loads is thought to be negligible. This depth is designed by Turkish Building Earthquake Code (TBEC, [3]) to be the highest of the two cases; (i) 1.5 times of the building width or (ii) the depth at which stress increment decreases to the 10% of the in-situ soil effective stress. For deep foundation applications, the investigation depth should be sufficient for the design of deep foundations.

Generally, one of the most widely acknowledged and used field test for soil characterization is Standard Penetration Test (SPT) [4]. This is due to its simplicity and convenience in its application. In addition, the test

---

[1] yusufkurtdereli@hotmail.com (Corresponding Author)

is done on undisturbed soils at the field, so the complexity encountered in the laboratory tests is avoided (i.e., taking undisturbed soil samples, transferring to the laboratory, forming the field conditions, replacing to the testing machines etc.). Besides, the parameter measured through SPT strongly reflects the load bearing capacity and settlement of the soils. In order to support the findings of SPT data, Cone Penetration and Menard Pressuremeter and Dilatometer Tests can be conducted. These tests mostly cause the development of large strains in the soil body, hence, offer a more reliable prediction of soil strength as opposed to soil stiffness [5].

Soil stiffness at small strain levels, on the other hand, is calculated with more accuracy by means of shear wave velocity (V_s). V_s measurement is seen to be significant especially in dynamic site response analysis, settlement analysis and soil-structure interaction [6-8]. There are two main in-situ V_s measurement techniques available: (1) surface wave methods and (2) subsurface wave methods. The most popular surface wave methods are multi-station analysis of surface wave (MASW) [9] and two-station spectral analysis of surface wave (SASW) [10], while down-hole and cross-hole methods are recognized to be widely used subsurface methods. Surface wave methods have several advantages over subsurface wave methods: (i) non-destructive and non-invasive, (ii) eases of test conduct and (iii) no need of opening boreholes (therefore its much cheaper and less time consuming). In surface wave techniques three main procedures carried out: (i) in-situ test involving records of the surface waves, (ii) featuring the dispersion in the measured field data and (iii) attaining shear wave velocity profile from the dispersion curve [11,12].

As SPT-N and V_s are two fundamental soil properties required for characterization of soil [13,14], correlation between these two parameters is always of interest. This is due to the fact that in the absence of one for a site, the other soil property can be predicted. For this purpose, $V_{s,30}$ map for Taiwan was generated by consistently configuring the relation of V_s with SPT-N over the 257 strong motion sites [15] . An empirical formulation was developed by [16] for the relationship between V_s and SPT-N varying over the depth of Alluvial and Pliocene soil deposits in Erbaa, Türkiye. Similarly, [17] suggested the correlation from the measurements of SPT-N and V_s values at 17 different locations in Lucknow city. Another empirical correlation between SPT-N and V_s measured via downhole tests was proposed by [18]. Unique empirical formulation for separate soils within the Roorkee area was proposed [19]. In addition, it was seen that the less the fine content available in the soil, the better the correlation becomes. Moreover, different correlations for various soil types (i.e. all soils, silty soils and sandy soils) were formed by taking into account 500 SPT-N and V_s values in the Kathmandu valley, Nepal [20]. [21] developed a set of correlations for various soil conditions in the Dholera territory by including 336 SPT-N and V_s data at, in total, 58 sites. [22] utilized measurements of SPT-N and V_s values at 20 boreholes in Edirne district, Türkiye, and tested the accuracy of available empirical formulations. Equally, using soil data from 30 different locations in Varanasi city, a correlation between SPT-N and V_s was recommended and seismic site classification was made available for the site of interest [23]. Similar studies offering different correlation between SPT-N and V_s for various sites and soil conditions can be found in the studies of Anbazhagan and Bajaj [24]; Kishida and Tsai [25]; Naji, Akin, and Cabalar [26]; Shukla and Solanki [27] and Rao and Choudhury [28] amongst others.

In the current study, it is attempted to develop best-fit curve between SPT-N and V_s for a region, within the Igdır district, Türkiye. The relationship is proposed for all soil types, clayey/silty soils, and sandy soils. Also, correlations between water content (w) and V_s and between liquid limit (LL) and V_s are configured. This paper carries on by defining the study area in the next section. Subsequently, detailed information regarding obtaining the SPT-N and V_s data is provided. Later, the correlations bounding SPT-N – V_s, w - V_s and LL - V_s are presented and discussed thoroughly. Finally, the main outputs of the study are briefly highlighted.

2. Location of the Study Area

The study area is within the Igdır district located far-east of Türkiye (Figure 1). The district borderline is colored blue (Figure 1a). It has borders with three seismically active countries; Armenia, Nakchivan and Iran. Igdır district including the study area of Melekli is positioned on a plain area deposited between Mount Ararat and Caucasus Mountains in the east of Türkiye. The study area is positioned approximately between 39^{0}60’0’’ and 39^{0} 56’0’’ latitudes and 44^{0}4’0’’ and 44^{0}7’0’’ longitudes, as demonstrated in Figure 1b. The soil bodies within the site are formed by quaternary alluvial soils as a result of depressions over the years from Aras River [29].

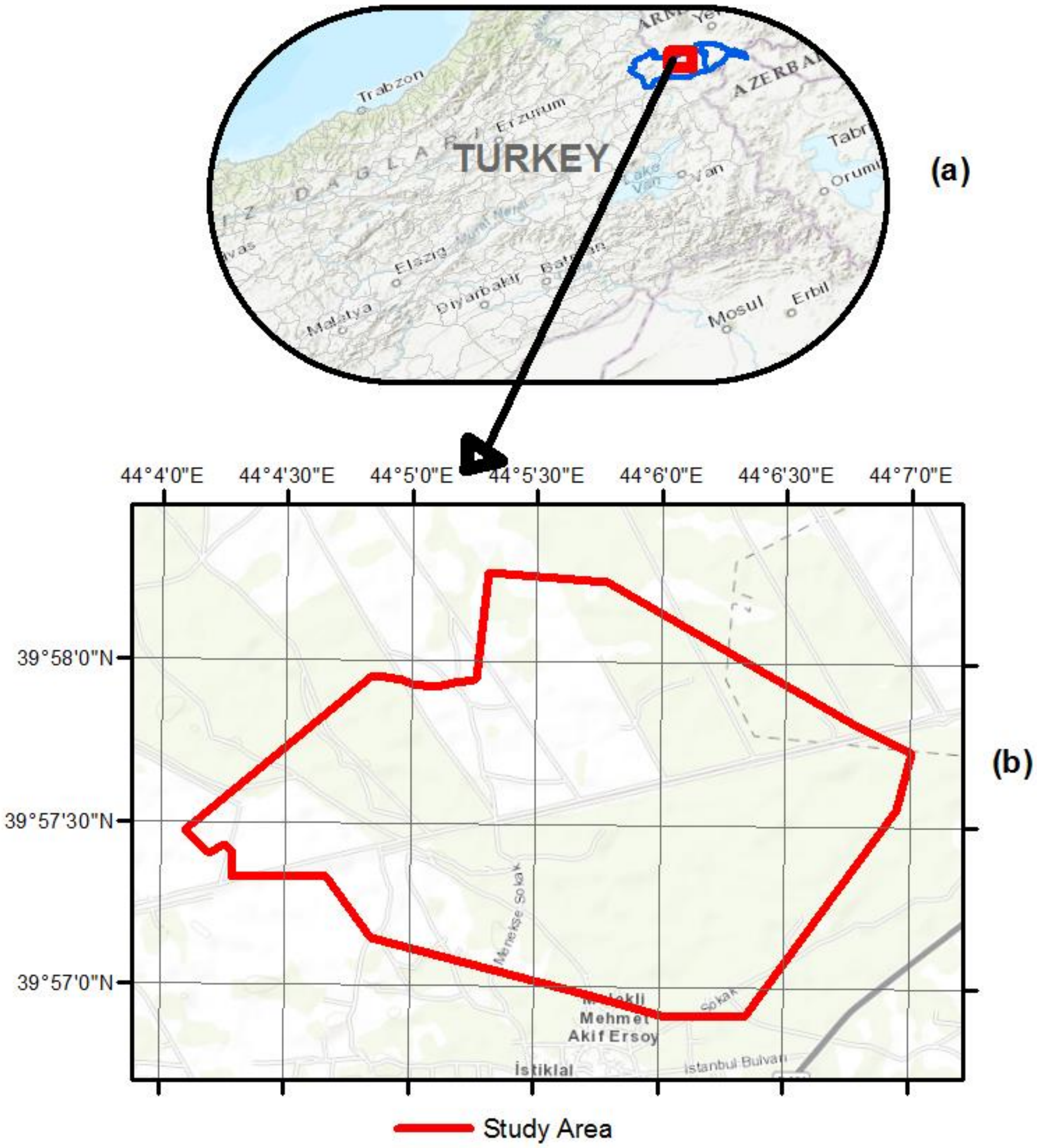


Figure 1. Location of the study area; (a) within Türkiye and Igdır district, bordering with Armenia, Nakhcivan and Iran, (b) with precise coordinates

3. SPT-N and Shear Wave Velocity Measurements

In the study area, 50 boreholes were opened to measure the SPT-N values in every 1.5 m depth at different locations. The field tests were conducted following TS-1900-1 [30] and SPT-N values are calculated accordingly. A fluid rotary drilling machine was used with $3^{5/8}$ inch drill. All of the boreholes reach 20 m depth while only 3 boreholes (BH-2, BH-49 and BH-50) opened up to 30 m depth from the ground surface. In total, 650 SPT-N data is considered from the opened boreholes. Locations of the boreholes are presented in Figure 2a. For the measurement of shear wave velocity (V_s) values throughout the depth, multi-station analysis of surface wave (MASW) method is used. In total, 26 MASW tests were conducted at locations distinctive than the borehole locations, as seen in Figure 2b. The V_s measurement at the locations were made up to 50 m below the ground surface.

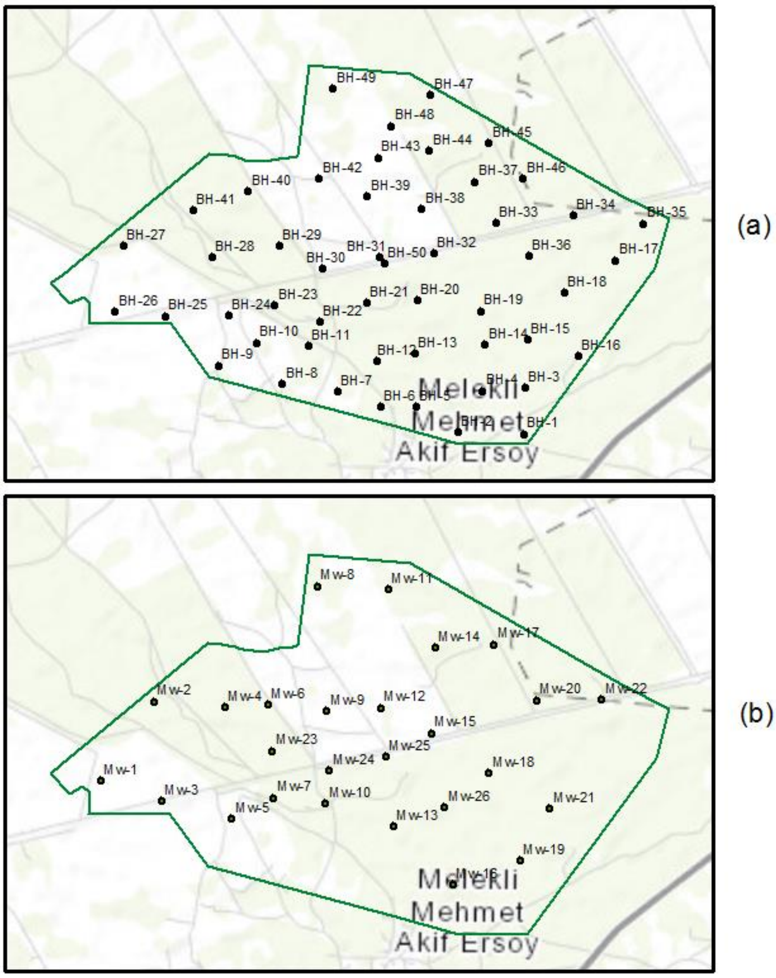
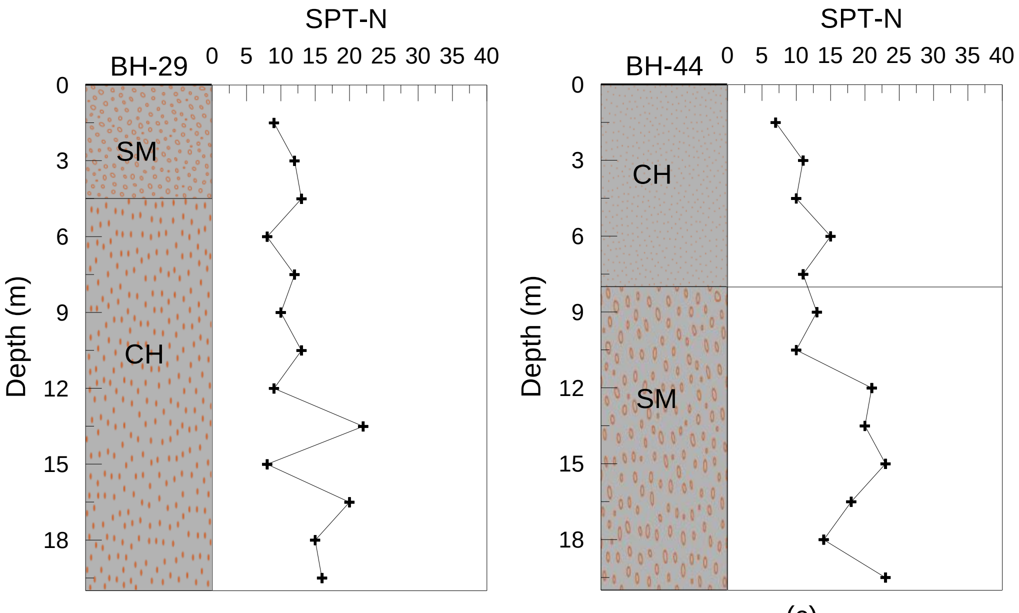


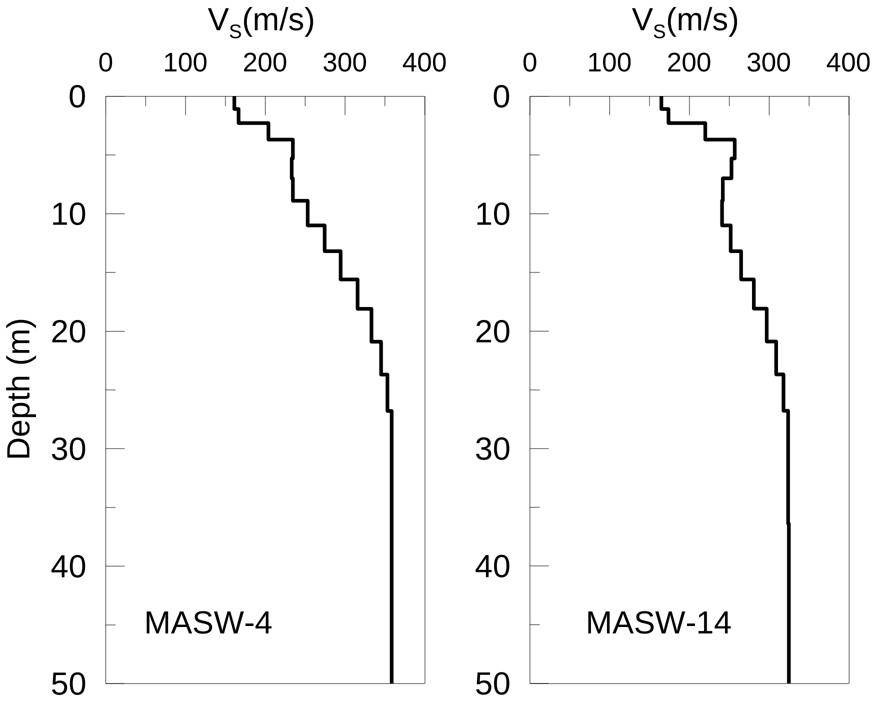
Figure 2. Locations of boreholes and MASW tests for a) SPT-N and b) shear wave velocity values

SPT-N values range from 3 to 49 within all the considered depths. SPT-N values at different depths for BH-29 and BH-44 are provided in Figure 3, aiming to demonstrate the exemplary stratigraphy and SPT-N distributions along 20 m depth in the study area. When the top 4.5 m is formed by silty sand, high plastic clay is seen up to 20 m depth in BH-29. Similarly, fine-grained highly plastic clay soil occupies the top 10.5 depth below which sand soil with silt inclusion is encountered in BH-44. In general, a majority of soil layers have fine-grained soils but there are still considerable coarse-grained soil layers available in the study area. V_s values also extend from 120 m/s to 345 m/s. Again, exemplary measured V_s values (or V_s profiles) and its changes along 50 m depth at two Mw locations are given in Figure 4. Minimum and maximum average V_s values at the top 30 m ($V_{s,30}$) are 188 m/s and 283 m/s, meaning that the investigated sites are most of the time classified as soil class C or soil class D according to Eurocode 8 [31] and Turkish Building Earthquake Code [3], respectively. The distribution of $V_{s,30}$ over the area of interest is illustrated in Figure 5.



(b) (c)

Figure 3. Distributions of SPT-N values until 20 m depth at BH-29 and BH-44



(a) (b)

Figure 4. V_s values up to 50 m depth at two different locations (MASW-4 and MASW-14)

Table 1. Ranges of average shear wave velocity at the top 30 m ($V_{s,\,30}$) of soil sites determining the soil classes given in EC8 and TBEC 2018

Design code/$V_{S,\,30}$ (m/s) range	>1500	760-1500	360-760	180-360	<180
EC8	A	B	C	D	
TBEC 2018	A	B	C	D	E

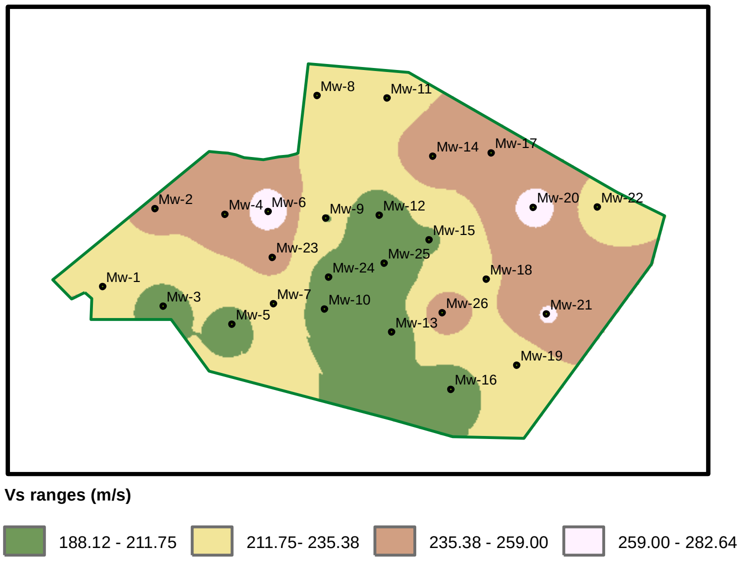


Figure 5. V_s distributions over the study area

It is important to note here that since the SPT-N and V_s measurement locations are different, the measured values cannot directly be correlated. Therefore, possible V_s values at SPT-N test locations are interpolated with inverse distance weight (IDW) method. The interpolation method estimates the desired values at a location from the measured values at known certain locations by allocating weight values based on their distances to the location of estimate. The idea of this method is the closer the distance between estimated and measured locations, the more likely the values will be similar [32]. Function governing the IDW interpolation is written as [33]:

$$Z(x) = \frac{\sum_{i=1}^{n} W_i Z_i}{\sum_{i=1}^{n} W_i} \tag{3.1}$$

$$W_i = d_i^{-u} \tag{3.2}$$

in which $Z(x)$ is the expected value at a location; Z_i is the known (measured) value at a known point; n is the total number of known values used in the interpolation; d_i is the distance between the known location and predicted location; and u is the weight power that expresses the development of weight decreases with the increase of the distances. The main component of the IDW interpolation is the power parameter, which is considered as 2. Several studies utilised IDW technique in mapping the SPT-N values along with the other soil parameters at a region. In this respect, [34] employed the Inverse Distance Weighting (IDW) technique to create spatial maps for soil type, Atterberg’s limits, sulphate and chloride content, and Standard Penetration Test (SPT-N) for the Sialkot district. [35] established geotechnical maps for the Lahore region, focusing on soil types and SPT-N values using GIS. [36] created contour maps for Islamabad based on N-values and soil types. Finally, [37] developed digital maps using GIS for Islamabad, showcasing geotechnical soil characteristics, vertical profiles, and bearing capacity curves for each zone.

Additionally, several laboratory tests were conducted to determine the soil types, limit states and Atterberg limits. Mainly, sieve analyses and hydrometer tests were conducted over, in total, 333 soil samples, Casagrande and plastic tests were made over 275 soil samples retrieved from the boreholes. Moreover, the water contents of the soil samples were attained. The soil layers consist mostly of fine-grained soils, accounting for 75% of the total soil bodies, and partially of coarse-grained soils, making up 25% of the total. The fine-grained soil layers contain low or high plastic clay and silt, with some gravel and sand. The coarse-grained soil layers are mainly composed of sand, with occasional gravel, silt, and clay. The plastic limit (PL) ranges from 26.2% to

77.9%, while the liquid limit (LL) ranges from 12.4% to 42.1%. The water content of the soils varies from 1.7% above the water table to a maximum of 57% below the water table. The soil densities measured range from 17.7 kN/m^3 to 19.2 kN/m^3.Overall, 72 and 261 soil samples possess sandy and clayey soil types, respectively.

4. Results and Discussion

4.1. Existing Empirical Formulations

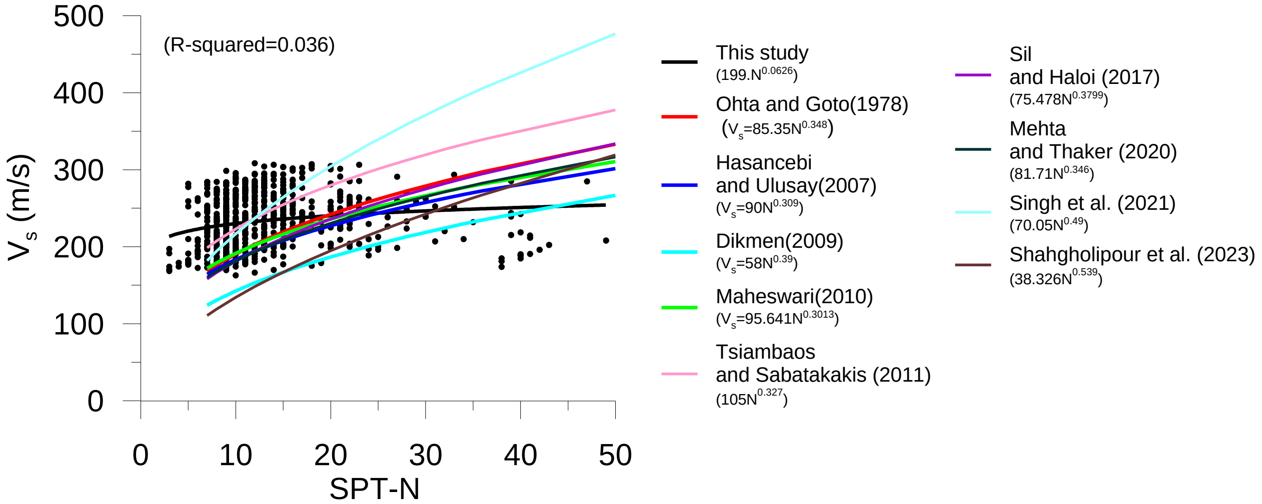
In literature, there have been numerous studies depicting the correlation between SPT-N and V_s data. Several empirical formulations given in the literature are presented in Table 2. These formulations totally involve uncorrected SPT-N values as uncorrected SPT-N values were thought to be strongly correlated with the V_s data. While in some studies the correlation was provided, separately, for all soils, sandy, silty, and clayey soils, others proposed only for all soils. Importantly, most of the time the suggested correlations were specific to the studied areas therefore does not necessarily suit the other locations [38]. Mostly, the prediction of V_s from SPT-N value is based on multiplication of a constant coefficient with powered SPT-N.

Table 2. Several existing empirical formulations representing the correlation between V_s and SPT-N given in the literature

Authors	All soils	Sand	Clay
Ohba and Toriumi [39]	$V_s=84N^{0.33}$	-	-
Athanasopoulos [40]	$V_s=107.6N^{0.36}$	-	$V_s=76.55N^{0.445}$
Ohsaki and Iwasaki [41]	$V_s=81.4N^{0.39}$	$V_s=59.4N^{0.47}$	-
Imai [42]	$V_s=91N^{0.337}$	$V_s=80.6N^{0.331}$	$V_s=102N^{0.292}$
Ohta and Goto [43]	$V_s=85.35N^{0.348}$	$V_s=88N^{0.34}$	-
Yokota, Imai, and Konno [44]	$V_s=121N^{0.27}$	-	-
Imai and Tonouchi [45]	$V_s=97N^{0.314}$	-	-
Jinan [46]	$V_s=116.1(N+0.3185)^{0.202}$	-	-
Lee [47]	-	$V_s=57.4N^{0.49}$	$V_s=144.43N^{0.31}$
Kalteziotis, Sabatakakis, and Vassiliou [48]	$V_s=76.2N^{0.24}$	$V_s=49.1N^{0.5}$	$V_s=76.6N^{0.45}$
Pitilakis, Anastasiadis, and Raptakis [49]	-	$V_s=162N^{0.178}$	-
Raptakis, Anastasiadis, Pitilakis, and Lontzetidis [50]	-	$V_s=100N^{0.24}$	$184.2N^{0.17}$
Kayabali [51]	-	$V_s= 175 + 3.5N$	-
Kyriazis Pitilakis, Raptakis, Lontzetidis, Tika-Vassilikou, and Jongmans [52]	-	$V_s=145N^{0.17}$	$V_s=162N^{0.178}$
Kiku [53]	$V_s=68.3N^{0.292}$	-	-
Hasancebi and Ulusay [54]	$V_s=90N^{0.309}$	$90.82N^{0.319}$	$97.89N^{0.269}$
Lee and Tsai [15]	$V_s=137.153N^{0.229}$	$V_s=98.07N^{0.305}$	$V_s=163.15N^{0.192}$
Dikmen [4]	$V_s=58N^{0.39}$	$73N^{0.33}$	$44N^{0.48}$
Maheswari, Boominathan, and Dodagoudar [55]	$V_s=95.641N^{0.3013}$	$100.53N^{0.263}$	$89.31N^{0.358}$
Tsiambaos and Sabatakakis [56]	$V_s=105.7N^{0.327}$	$V_s=79.7N^{0.365}$	$V_s=88.8N^{0.37}$
Anbazhagan et al. [38]	$V_s=68.96N^{0.51}$	$V_s=60.17N^{0.56}$	$V_s=106.63N^{0.39}$
Sarda Thokchom et al. [21]	$V_s=3.39N+160.5$	-	-
Sil and Haloi [57]	$V_s=75.478N^{0.3799}$	$V_s=79.217N^{0.369}$	$V_s=99.708N^{0.335}$
Mehta and Thaker [58]	$V_s=81.71N^{0.346}$	$V_s=79.81N^{0.355}$	$V_s=83.65N^{0.336}$
Singh, Duggal, and Singh [23]	$V_s=70.05N^{0.49}$	-	$V_s=74.80N^{0.47}$
Shahgholipour, Afsari, and Ghaseminejad [59]	$V_s=38.726N^{0.539}$	$V_s=42.515N^{0.496}$	$V_s=31.241N^{0.626}$

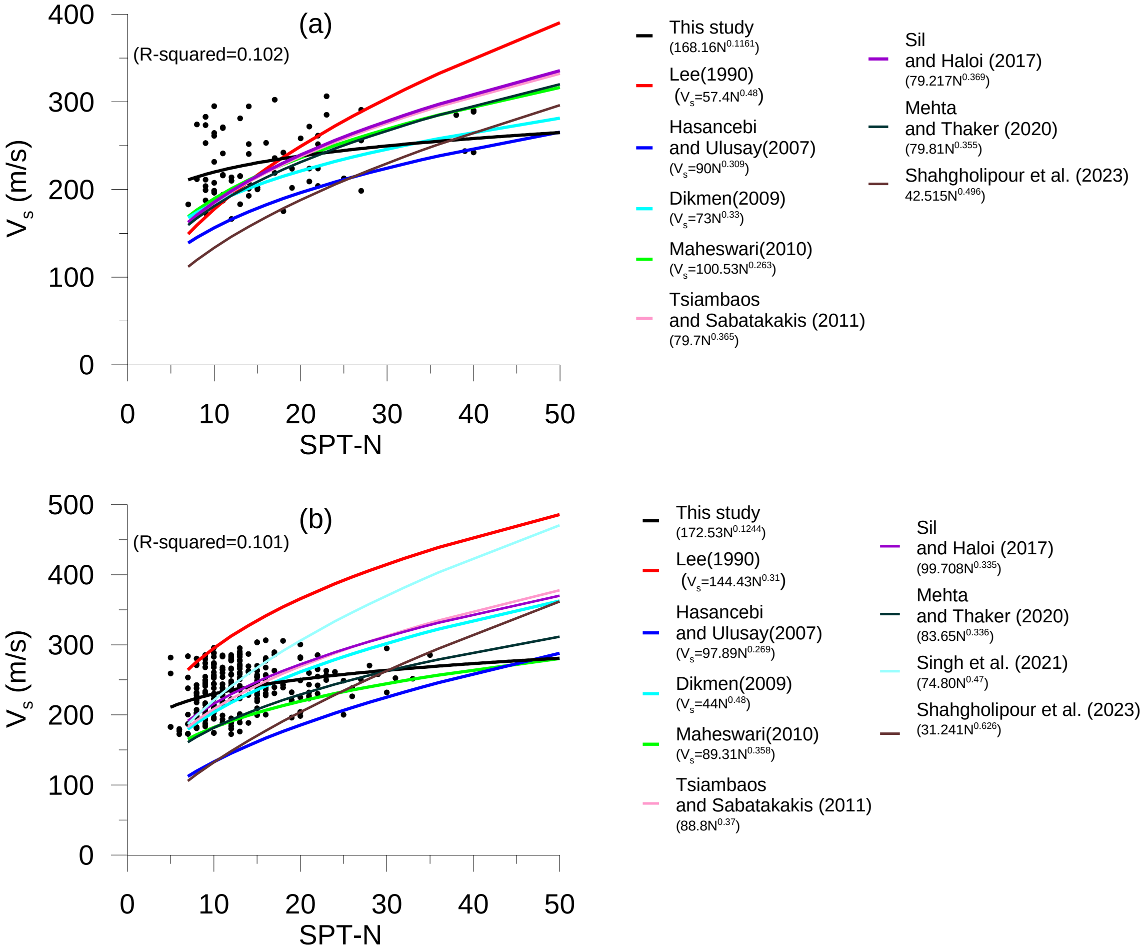
4.2. Proposed Empirical Formulations

In Figure 6, pairs of SPT-N and V_s values at the same depths are presented along with the best-fit curve for all soils. In addition, the ten developed curves belonging to the empirical formulations available in the literature are plotted. The correlation within the observed data in the studied site seems to be flat. More clearly, the increase in the SPT-N data does not tend to increase the V_s drastically. Instead, it is possible to see alike V_s values for small and large SPT-N values. Therefore, the best-fit curve possesses a higher coefficient with less power value. In contrast, the curves provided in the literature are developing more linearly and they tend to smooth with the higher SPT-N values. The curves suggested by Ohta and Goto [43], Hasancebi and Ulusay [54] and Maheswari et al. [55] give always lower V_s values up to the SPT-N values of 20-25 than the best-fit curve of the available data. Above these SPT-N values, V_s predicted by the aforementioned curves are always greater than the suggestions by the current data best-fit curve. Besides, the empirical correlation suggested by Sil and Haloi [57] almost overlaps with that of Ohta and Goto [43], in particular when SPT-N value is over 30. Similarly, Mehta and Thaker [58] empirical correlation performs in line with that of Hasancebi and Ulusay [54]. The correlation produced by Dikmen [4] gives lower V_s than the best-fit from this study and from the others below the SPT-N value of 45. The empirical correlation given by Tsiambaos and Sabatakakis [56] predicts V_s values that are second highest in the plotted curves after Dikmen [4]. On the contrary, the correlation produced by Singh et al. [23] expresses the lowest V_s values against SPT-N values, especially between 16 and 44 SPT-N range, and does not match with the best-fit curve of the current data. Lastly, the suggested empirical correlation by Shahgholipour et al. [59] depicts V_s values incrementing gradually but still lower than the best fit curve up to the SPT-N value of 30.

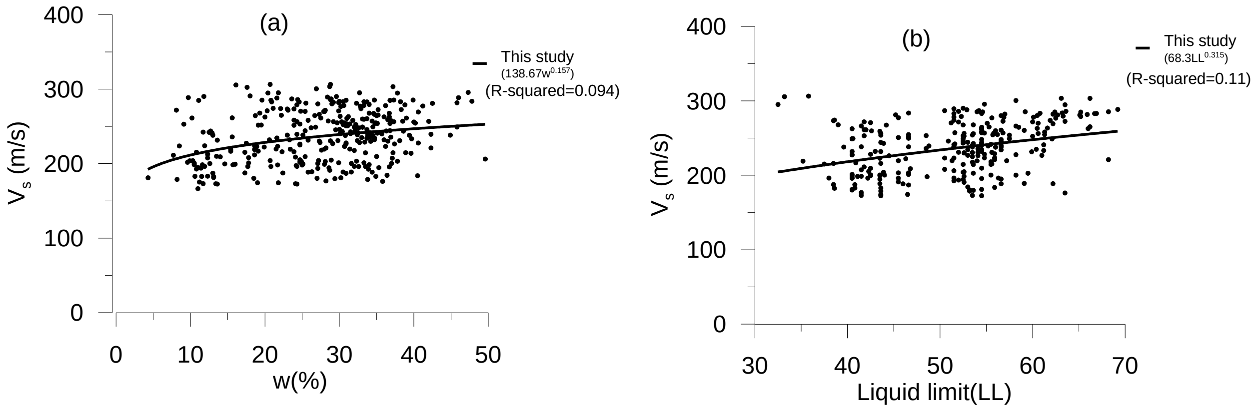


Figures 6. Best-fit curve representing the correlation, for all soils) between SPT-N and V_s data at the study site along with the suggested curves available in the literature

In Figures 7a and 7b, the correlations are separately assessed for sandy and clayey soils, respectively. Again, 9 and 10 different correlations for sandy and clayey soils given in the literature are also demonstrated for comparison purposes. The correlations proposed by Lee [47], Hasancebi and Ulusay [54], Dikmen [4] and Maheswari et al. [55] offer V_s values that are well below the best-fit curve of this study until approximately 16, 20, 34 and 50 SPT-N values (as seen in Figure 7a). Above the mentioned SPT-N values, the literature given empirical correlations always predict higher V_s values. It is, however, important to note that the inclinations of the curves by Hasancebi and Ulusay [54] and Dikmen [4] get closer to the best-fit curve of the current data by the increase of the SPT-N value. The empirical correlations by Maheswari [55] and Mehta and Thaker [58] and by Tsiambaos and Sabatakakis [56] and Sil and Haloi [57] result in almost same V_s predictions when the formers lead to greater V_s values than the latter ones, particularly above the SPT-N value of 20.5. The suggested empirical correlation by Shahgholipour et al. [59] estimates always less V_s values up to the SPT-N value of 37.6 than the best-fit curve of the current data, above which it leads to the higher values. Similar comments can also be made for the correlations proposed by clayey soils. Nevertheless, the correlations recommended by Lee [47] and Singh et al. [23] are totally out of the given data, producing always higher V_s values (Figure 7b). In this case, the correlations proposed by Hasancebi and Ulusay [54] Maheswari [55] and Mehta and Thaker [58] incline nearer to the best-fit curve of the current data.



Figures 7. Best-fit curve representing the correlations, for (a) sandy and (b) clayey soils, between SPT-N and V_s data at the study site along with the suggested curves available in the literature



Figures 8. Correlations between (a) V_s and w and (b) V_s and LL and their best-fit curves

Predicting the V_s from the water content (w) and from the liquid limit (LL) values are also possible. Since w and LL are available for 333 and 275 soil samples, their relations with the V_s data are plotted in Figures 8a and 8b, respectively, along with the best-fit curves. While the best-fit curve for the V_s-w correlation is information of V_s=138.67w$^{0.157}$, and for the V_s-LL correlation it is represented by V_s=68.3LL$^{0.315}$. These formulations, in addition to the previously represented ones, are illustrated in Table 3.

Table 3. Relation of V_s with SPT-N and w values for all soils, sandy soils, and clayey soils

Correlation type	For all soils	For sandy soil	For clayey soil
V_s - SPT-N	199N$^{0.0626}$	168.16N$^{0.1161}$	68.3N$^{0.315}$
V_s - w	138.67w$^{0.157}$	-	-
V_s - LL	-	-	68.3LL$^{0.315}$

The correlations between SPT-N and V_s values at the studied site depicted for all soils and sandy and clayey soils are shown to be unique to this site as the empirical correlations available in the literature do not match well with the current data. In fact, the correlations in the literature also divert mostly from each other. The suggested SPT-N and V_s correlations (as well as V_s-w and V_s-LL correlations) can be useful for future site studies that may be conducted in future. They will be useful to obtain knowledge of SPT-N values and stiffness distribution for the site that are main inputs for calculating soil bearing capacity and site response analysis.

5. Conclusion

This study evaluates and proposes the correlation between V_s and SPT-N values measured at the Melekli region deposited by alluvial soils, in Türkiye. Correlations are formed for all soils, sandy soils, and clayey soils. Several existing well-known V_s prediction equations are also used for comparison purposes. In addition, the formulations for the prediction of V_s through the measured w and LL values at the site are suggested. The results of this study can be listed as follows:

- The best-fit curve representing the correlation between the V_s and SPT-N for the site is relatively flatter than the ones given in the literature for all soils.

- Similarly, the best-fit curves in the case of sand and clay soils divert considerably from the correlations given in the literature. This is, in particular, true at low SPT-N values as the diversion diminishes at higher SPT-N values with two of the existing correlations.

- In fact, the suggested correlations are significantly dissimilar in any types of soils. This can be attributed to the unique geological conditions (formations, effective stress, overconsolidation, etc) that lead to the formations of distinctive correlations between V_s and SPT-N values.

- For the studied site, it has been shown that w and LL are correlated, to some extent, with V_s as much as that correlation level with SPT-N.

Overall, development of correlation between V_s and SPT-N for a specific site cannot suit to another site. Finally, the significance of such correlation may alter from one site to another and different soil parameters (like w, LL, etc.) may also correlate reasonably well with V_s or SPT-N.

Author Contributions

The author read and approved the final version of the paper.

Conflicts of Interest

The author declares no conflict of interest.

Acknowledgement

The author thanks Dr. Muhammed Alperen Özdemir at Iğdır University (Türkiye) for attaining the geotechnical data and the Turkish Special Provincial Administration (Iğdır) for sharing the data.

References

[1] Ö. Yıldız, *Correlation between Spt and Pmt results for sandy and clayey soils*, Eskişehir Technical University Journal of Science Technology A-Applied Sciences 22 (2) (2021) 175–188.

[2] S. L. Kramer, Geotechnical earthquake engineering, Simon & Schuste, New Jersey, 1996.

[3] Turkish Building Earthquake Code, Deprem etkisi altında binaların tasarımı içn esaslar (in Turkish), Türkiye bina deprem yonetmeligi, Ankara, 2018.

[4] Ü. Dikmen, *Statistical correlations of shear wave velocity and penetration resistance for soils*, Journal of Geophysics and Engineering 6 (1) (2009) 61–72.

[5] C. P. Lin, C. H. Lin, C. J. Chien, *Dispersion analysis of surface wave testing - SASW vs. MASW*, Journal of Applied Geophysics 143 (2017) 223–230.

[6] Y. Guzel, F. Guzel, *Investigation of local site effect considering the recordings of the 08.11.2021 earthquake event in Konya, Turkey*, Natural Hazards 116 (1) (2023) 619–636.

[7] Y. Guzel, M. Rouainia, G. Elia, *Effect of soil variability on nonlinear site response predictions: Application to the Lotung site*, Computers and Geotechnics 121 (2020) 103444 16 pages.

[8] K. H. Stokoe, S. H. Joh, R. D. Woods, *Some contributions of in situ geophysical measurements to solving geotechnical engineering problems*, 2nd International Conference on Site Characterization (ISC-2), Porto, 2004, 19–22.

[9] C. B. Park, R. D. Miller, J. H. Xia, *Multichannel analysis of surface waves*, Geophysics 64 (3) (1999) 800–808.

[10] S. Nazarian, K. H. Stokoe II, *In situ shear wave velocities from spectral analysis of surface waves*, Proceedings of the Eight World Conference on Earthquake Engineering, San Francisco, 1984, pp. 31–40.

[11] C. P. Lin, C. C. Chang, T. S. Chang, *The use of MASW method in the assessment of soil liquefaction potential*, Soil Dynamics and Earthquake Engineering 24 (9-10) (2004) 689–698.

[12] S. Nazarian, M. R. Desai, *Automated Surface-Wave Method - field testing*, Journal of Geotechnical Engineering-Asce 119 (7) (1993) 1094–1111.

[13] P. Anbazhagan, K. Ayush, M. E. Yadhunandan, K. Siriwanth, K. Suryanarayana, G. Sahodar, *Effective use of SPT: Hammer energy measurement and integrated subsurface investigation*, Indian Geotechnical Journal 52 (5) (2022) 1079–1096.

[14] K. S. Vipin, T. G. Sitharam, P. Anbazhagan, *Probabilistic evaluation of seismic soil liquefaction potential based on SPT data*, Natural Hazards 53 (3) (2010) 547–560.

[15] C.-T. Lee, B.-R. Tsai, *Mapping Vs30 in Taiwan*, Terrestrial Atmospheric and Oceanic Sciences 19 (6) (2008) 671–682.

[16] M. K. Akin, S. L. Kramer, T. Topal, *Empirical correlations of shear wave velocity (Vs) and penetration resistance (SPT-N) for different soils in an earthquake-prone area (Erbaa-Turkey)*, Engineering Geology 119 (1-2) (2011) 1–17.

[17] P. Anbazhagan, *Method for seismic microzonation with geotechnical aspects*, Disaster Advances 6 (4) (2013) 66–85.

[18] M. Esfehanizadeh, F. Nabizadeh, R. Yazarloo, *Correlation between standard penetration (N-SPT) and shear wave velocity (Vs) for young coastal sands of the Caspian Sea*, Arabian Journal of Geosciences 8 (9) (2015) 7333–7341.

[19] B. Kirar, B. K. Maheshwari, P. Muley, *Correlation between shear wave velocity (Vs) and SPT resistance (N) for Roorkee Region*, International Journal of Geosynthetics and Ground Engineering 2 (2016) Article Number 9 11 pages.

[20] D. Gautam, *Empirical correlation between uncorrected standard penetration resistance (SPT-N) and shear wave velocity (Vs) for Kathmandu Valley, Nepal*, Geomatics Natural Hazards and Risk 8 (2) (2017) 496–508.

[21] S. Thokchom, B. Rastogi, N. Dogra, V. Pancholi, B. Sairam, F. Bhattacharya, V. Patel, *Empirical correlation of SPT blow counts versus shear wave velocity for different types of soils in Dholera, Western India*, Natural Hazards 86 (2017) 1291–1306.

[22] K. Dehghanian, E. Çaltılı, B. Koçak, H. M. Soysal, *Implementation of shear wave velocity and standard penetration test correlation for Edirne district, Turkey*, Journal of Sustainable Construction Materials 7 (1) (2022) 24–29.

[23] M. Singh, S. K. Duggal, V. P. Singh, *A Study to establish regression correlation between shear wave velocity and "N"-Value for Varanasi City, India*, Proceedings of the National Academy of Sciences India Section a-Physical Sciences 91 (2) (2021) 405–417.

[24] P. Anbazhagan, K. Bajaj, *Region-specific correlations between VS30 and time-averaged VS and SPT-N values at different depths for the indo-gangetic basin*, Indian Geotechnical Journal 50 (3) (2020) 454–472.

[25] T. Kishida, C. C. Tsai, *Prediction model of shear wave velocity by using SPT blow counts based on the conditional probability framework*, Journal of Geotechnical and Geoenvironmental Engineering 143 (4) (2017) 10 pages.

[26] D. M. Naji, M. K. Akin, A. F. Cabalar, *A comparative study on the V_{S30} and N_{30} based seismic site classification in Kahramanmaras, Turkey*, Advances in Civil Engineering 2020 (2020) Article ID 8862827 15 pages.

[27] D. Shukla, C. H. Solanki, *Estimated Empirical Correlations Between Shear Wave Velocity and SPT-N Value for Indore City Using NLR and ANN*, Indian Geotechnical Journal 50 (5) (2020) 784–800.

[28] V. D. Rao, D. Choudhury, *Estimation of shear wave velocity and seismic site characterization for new nuclear power plant region, India*, Natural Hazards Review 21 (4) (2020) 11 pages.

[29] M. Öztürk, V. Altay, E. Altundağ, S. Gücel, Halophytic plant diversity of unique habitats in Turkey: Salt mine caves of Çankırı and Iğdır, Halophytes for food security in dry lands, Elsevier, Oxford, 2016, pp. 291–315.

[30] TS 1900-1, İnşaat mühendisliğinde zemin laboratuvar deneyleri, Bölüm 1: Fiziksel özelliklerin tayini, Ankara, 2006.

[31] CEN, Eurocode 8: Design of structures for earthquake resistance–Part 1: General rules, seismic actions and rules for buildings, Brussels, 2005.

[32] G. S. Bhunia, P. K. Shit, R. Maiti, *Comparison of GIS-based interpolation methods for spatial distribution of soil organic carbon (SOC),* Journal of the Saudi Society of Agricultural Sciences 17 (2) (2018) 114–126.

[33] Y. F. Xie, T. B. Chen, M. Lei, J. Yang, Q. J. Guo, B. Song, X. Y. Zhou, *Spatial distribution of soil heavy metal pollution estimated by different interpolation methods: Accuracy and uncertainty analysis*, Chemosphere 82 (3) (2011) 468–476.

[34] Z. Ijaz, C. Zhao, N. Ijaz, Z. ur Rehman, A. Ijaz, *Spatial mapping of geotechnical soil properties at multiple depths in Sialkot region, Pakistan,* Environmental Earth Sciences, 80 (2021) Article Number 787 16 pages.

[35] H. U. Khan, I. Rashid, J. Israr, G. Zhang, *Geotechnical characterization and statistical evaluation of alluvial soils of Lahore*, Arabian Journal of Geosciences 15 (2022) Article Number 845 12 pages.

[36] M. H. Khalid, B. Alshameri, U. Abid, *Application of Kriging for development of SPT N value contour maps and USCS-based soil type qualitative contour maps for Islamabad, Pakistan*, Environmental Earth Sciences 80 (2021) Article Number 413 13 pages.

[37] W. Hassan, B. Alshameri, M. N. Nawaz, Z. Ijaz, M. Qasim, *Geospatial and statistical interpolation of geotechnical data for modeling zonation maps of Islamabad, Pakistan*, Environmental Earth Sciences 81 (2022) Article Number 547 23 pages.

[38] P. Anbazhagan, A. Parihar, H. N. Rashmi, *Review of correlations between SPT-N and shear modulus: A new correlation applicable to any region,* Soil Dynamics and Earthquake Engineering 36 (2012) 52–69.

[39] S. Ohba, I. Toriumi, *Dynamic response characteristics of Osaka Plain (in Japanese)*, Proceedings of the Annual Meeting AIJ, Tokyo, 1970.

[40] G. Athanasopoulos, *Empirical correlations Vso-NSPT for soils of Greece: A comparative study of reliability*, Transactions on The Built Environment 15 (1970) 8 pages.

[41] Y. Ohsaki, R. Iwasaki, *On dynamic shear moduli and Poisson's ratios of soil deposits*, Soils & Foundations 13 (4) (1973) 61–73.

[42] T. Imai, *P and S wave velocities of the ground in Japan*, 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo, 1977, pp: 257–260.

[43] Y. Ohta, N. Goto, *Empirical shear wave velocity equations in terms of characteristic soil indexes*, Earthquake Engineering & Structural Dynamics 6 (2) (1978) 167–187.

[44] K. Yokota, T. Imai, M. Konno, *Dynamic deformation characteristics of soils determined by laboratory tests*. OYO Tec. Rep 3 (1981) 13–37.

[45] T. Imai, K. Tonouchi, *Correlation of N-value with S-wave velocity*, Proceedings of 2. European Symposium on Penetrating Testing, Amsterdam, 1982.

[46] Z. Jinan, Correlation between seismic wave velocity and the number of blow of SPT and depth, Chinese Journal of Geotechnical Engineering, American Society of Civil Engineers, USA, 1987, pp. 92–100.

[47] S. H. H. Lee, *Regression models of shear wave velocities in Taipei basin*, Journal of the Chinese Institute of Engineers 13 (5) (1990) 519–532.

[48] N. Kalteziotis, N. Sabatakakis, J. Vassiliou, *Evaluation of dynamic characteristics of Greek soil formations (in Greek),* Second Hellenic Conference on Geotechnical Engineering, 1992, pp. 239–246.

[49] K. Pitilakis, A. Anastasiadis, D. Raptakis, *Field and laboratory determination of dynamic properties of natural soil deposits,* 10th World Conference on Earthquake Engineering, Balkema, 1992, pp. 1275–1280.

[50] D. Raptakis, S. Anastasiadis, K. Pitilakis, K. Lontzetidis, *Shear wave velocities and damping of Greek natural soils,* in: G. Duma, 10th European Conferance Earthquake Engineering, Vienna, 1995, pp. 477–482.

[51] K. Kayabali, *Soil liquefaction evaluation using shear wave velocity*, Engineering Geology 44 (1-4) (1996) 121–127.

[52] K. Pitilakis, D. Raptakis, K. Lontzetidis, T. Tika-Vassilikou, D. Jongmans, *Geotechnical and geophysical description of EURO-SEISTEST, using field, laboratory tests and moderate strong motion recordings*, Journal of Earthquake Engineering 3 (03) (1999) 381–409.

[53] H. Kiku, *In-situ penetration tests and soil profiling in Adapazari, Turkey,* 15th ICSMGE TC4 Satellite Conference on Lessons Learned from Recent Strong Earthquakes, İstanbul, 2001, pp. 259–265.

[54] N. Hasancebi, R. Ulusay, *Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments*, Bulletin of Engineering Geology and the Environment 66 (2) (2007) 203–213.

[55] R. U. Maheswari, A. Boominathan, G. R. Dodagoudar, *Use of surface waves in statistical correlations of shear wave velocity and penetration resistance of chennai soils*, Geotechnical and Geological Engineering 28 (2) (2010) 119–137.

[56] G. Tsiambaos, N. Sabatakakis, *Empirical estimation of shear wave velocity from in situ tests on soil formations in Greece*, Bulletin of Engineering Geology the Environment 70 (2011) 291–297.

[57] A. Sil, J. Haloi, *Empirical correlations with standard penetration test (SPT)-N for estimating shear wave velocity applicable to any region*, International Journal of Geosynthetics and Ground Engineering 3 (2017) Article Number 22 13 pages.

[58] P. Mehta, T. Thaker, *Development Of correlations between shear wave velocity and Spt-N for Vadodara Region, Gujarat, India*, Journal of GeoEngineering 15 (3) (2020) 145–157.

[59] F. Shahgholipour, N. Afsari, V. Ghaseminejad, *Correlation between shear wave velocity and standard penetration test for Nowshahr and Chalus, Iran*, Iranian Journal of Geophysics 17 (6) (2023) 37–52.