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Utilizing seismic techniques and dynamic field tests for soil dynamic response prediction in clay soils

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Abstract. When evaluating the dynamic response of soil, shear modulus is an essential parameter to consider. In most cases, the shear modulus is estimated using the shear wave velocity (Vs) of the soil as observed in field geophysical testing. Consequently, shear modulus is the main parameter for geotechnical earthquake engineering problems, both quantitatively and qualitatively. Its measuring must be done meticulously. In many cases, however, the shear wave velocity may be predicted using field dynamic tests such as the Standard Penetration Test (SPT) N-value of soil when direct measurements of Vs are unavailable. There are various empirical formulae that associate soil type and SPT N-value to predict the shear wave velocity. On the other hand, all of these equations are based on several field observations related to specific places and geology. In this paper, different approaches for estimating the actual shear wave velocity measurements from SPT data were clarified and compared. The data of 59 boreholes in Al Nasiriya's soil investigation were used. The standard penetration test data computations were applied. The current study investigated and possessed shear wave velocity based on SPT N-values using the Excel application, then represented it in the Geographical Information System (GIS) and compared it with geophysical exploration. The SPT-Vs correlation generated for Al Nasiriya, Iraq, demonstrated a better degree of fitness for the dataset. There was also a suggestion for a site-specific SPT-Vs connection. On the other hand, most of the SPT-Vs expressions evaluations indicated a valuable predictive ability.

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1. Introduction

Native soil strongly affects the amplification of seismic waves produced by earthquakes. Many earthquakes have confirmed this reality throughout the last century. Ground response calculations that solely include upward propagating shear waves are commonly used to estimate the ground motion parameters at the surface. The shear wave velocity (Vs) is one of the most essential input factors in these assessments for representing the stiffness of native soil layers. In comparison to the other in situ approaches, measuring shear wave velocity in the field is preferable. However, due to space limitations and the high noise levels associated with these tests, it is frequently not economically feasible to conduct the shear wave velocity measurement in all circumstances, especially in civil areas. In geotechnical engineering, the standard penetration test (SPT) is connected to a number of soil design parameters. The shear wave (Vs) must therefore be determined indirectly, such as via the SPT test [1]. Theoretically, there is no connection between destructive processes (such as SPT) and non-destructive ones (e.g., seismic methods). As a result, numerous studies have been conducted to assess the geotechnical characteristics of the soil and to discover empirical correlations between SPT N and Vs qualities. Numerous researchers have suggested an experimental relation between SPT N and Vs since 1970 even now. Hossain et al. [2], explained that the number of borehole data sets required to determine shear wave velocity is important. The regression curves would be more accurate if there were additional borehole datasets. Some coefficients were decreased due to a lack of data, the number of equations utilized, and other causes. The regression equation generated by calculating Vs from SPT blow count provides a viable alternative to real field data that may be utilized for preliminary seismic microzonation and seismic site response for the research region [2]. According to Hasan et al. [3], a new formulation of the equation between Vs and N has been presented, and it is able to accurately forecast the values of Vs. The proposed equation was put to the test again using a sizable dataset in Erbil city to see how well it predicts the future [3]. Additionally, various correlations were formed on the zones of a region and presented for specific ranges of Vs. A chronological overview of the numerical link between SPT N and shear waves was reported by Jafari et al. [4]. For all soil types, with the exception of gravel, Hasancebi and Ulusay [5] investigated similar numerical correlations and superior empirical relationships using 97 data sets obtained from a location in the north-western region of Turkey. The experience connection was defined as upper and lower boundaries rather than an average curve for computing seismic velocities and relative density by researchers in Turkey using 327 samples collected from various places. In order to estimate seismic velocities and relative density, Ulugergerli and Uyank [6] used 327 samples gathered from various regions of Turkey to study statistical correlations. They described the experience correlation as lower and upper bounds rather than a single average curve. According to Eq. (1), 200 data pairs of the shear wave velocity (Vs) and SPT N collected at 50 Chennai locations, largely made up of very soft to highly stiff clay and very loose to dense sand, showed a correlation between each other [7]:

$$Vs = 95.64 \cdot N^{0.301}. \tag{1}$$

In-situ tests in Greece were used to estimate the shear wave velocity using empirical data. Soil type appears to play a significant role in these connections, as different patterns were detected for different soil groups. Clays and marls have Vs-values up to 25 per cent greater than sandy soils, while soft and loose soils (N_{60}) have Vs-values up to 30 per cent higher than sandy soils. Using a corrected final blow count $(N1)_{60}$ may have caused the low R^2-values, which may have overemphasized the overburden issue (CN) [8]. For the appropriate design, construction, and operation of all sorts of geotechnical projects, including foundations, earth dams, embankments, excavation, and seismic hazards, geotechnical subsurface knowledge is necessary. GIS-based maps and contour maps can be used to represent geotechnical subsurface information, such as soil N value, soil classification, and water table. For assessing geotechnical earthquake engineering challenges, including site-specific amplification factor and ground reaction analysis, SPT N-value and shear wave velocity are crucial input factors. The most popular method for obtaining shear wave velocity (Vs) data is borehole logging, but it is expensive and challenging to drill and log to the depths needed for seismic ground motion research [9]. Even though GIS-based maps have many limitations, foundation designers will find them helpful in both static and seismic circumstances during the early stage of site selection. Subsurface investigations are less common in low-cost home complexes, but they can be used in those as well [10]. A collection of Thematic Maps for the soil variation in Bearing Capacity was developed Using SPTs and MATLAB for the important Iraqi city of Al-Basrah. Drilling 135 boreholes down 10 meters below the surface of the ground as part of the soil survey. The first-order polynomial was the most effective among the other trials despite the fact that several-order interpolation polynomials were utilized to calculate the bearing capacity of the soil. The reason for this is that it is simple and has quick calculations [11]. The development of thematic maps illustrates how driven pile-bearing capacities vary over the whole Al-Basrah Governorate with respect to various depths. The outcomes of the statistical equations demonstrated that the results and those obtained from the SPT data are in good agreement [12].

Also, for each of the models that were tried, the Root Mean Squared Error (RMSE) was essentially the same.

The objective of this study is determination of the SPT N-values and Vs empirical correlations for Thi-Qar regime in Iraq. Cross-hole experiments were carried out at four places in Thi-Qar to generate the shear wave velocity profiles. Geotechnical boreholes were used to verify the data. The statistical analysis of the data was conducted. To take into account soil type, a set of empirical relationships for forecasting shear-wave velocity from SPT N were created.

2. *Methods*

2.1. *Site Geology and Seismicity of The Studied Area*

Specifically, this research focuses on the southern Iraqi city of Nasiriya, the administrative headquarters of Thi-Qar Province. Nasiriya is an oil city producing conventional oil. The Mesopotamian sediments that cover the city's foundation include flood plain deposits, fluvial deposits, marsh deposits, and Aeolian deposits, as seen in Fig. 1 [13].

Figure 1. Tectonic setting of Iraq and environs [14].

The area of study represents selected 59 boreholes from Al-Nasiriyah metropolis dispensed on each side of the Euphrates River, as shown in Fig. 2.

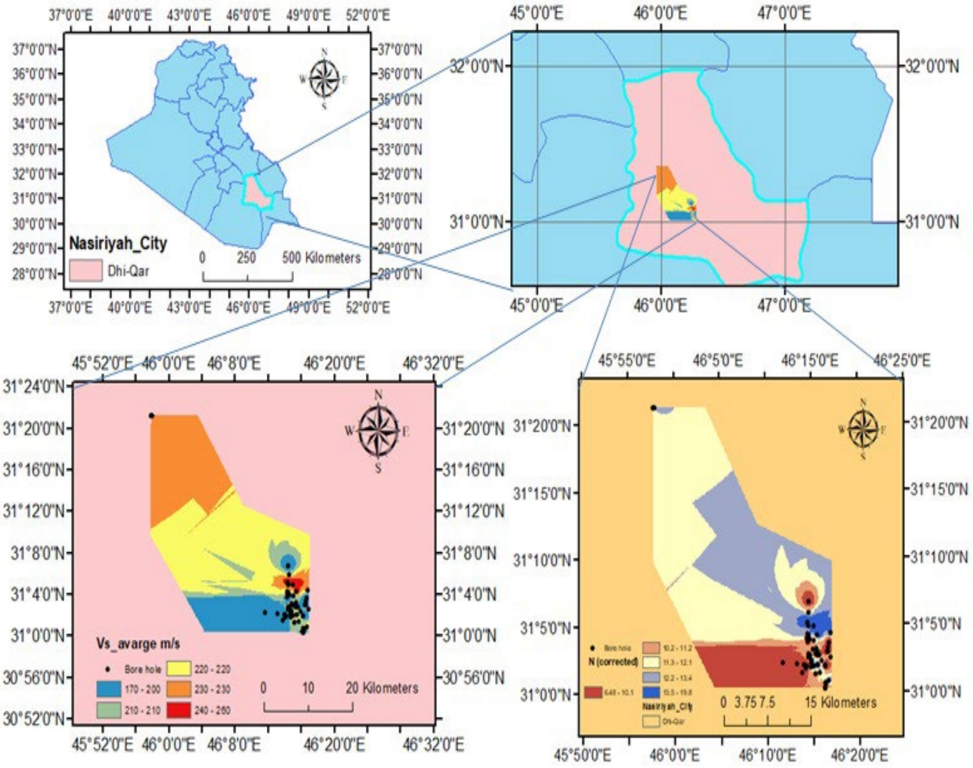

Figure 2. Location of geotechnical and seismic investigation in the study site.

The Arabian plate's northeastern border, where Iraq lies, is a seismically active location. It is clear from the country's seismic records that earthquakes occurred with greater frequency in Iraq's northern and northeastern regions and the country's southern and southwest regions, but these earthquakes were much less potent than those in Iraq's northern, northeastern regions, as shown in Fig. 3 [15, 16].

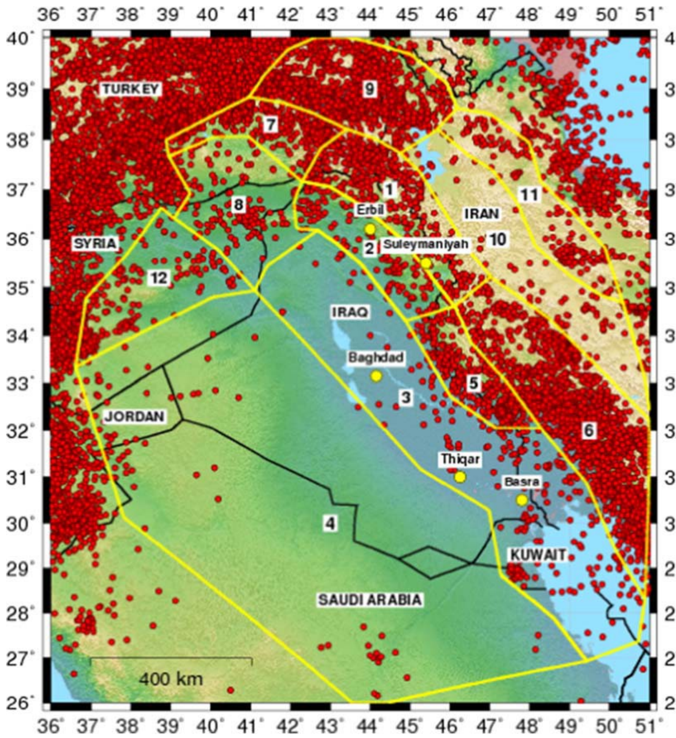

Figure 3. Delineation of seismic source zones in Iraq and adjacent areas [13].

As Jassim and Goff have argued, the Mesopotamian region of volatile shelves includes the city of Nasiriya, which sits within the Euphrates subzone of the Mesopotamian solid shelf. According to the seismic zoning chart, Al-Nasiriya is a no-destruction zone. Fig. 4 shows this clearly [14–20].

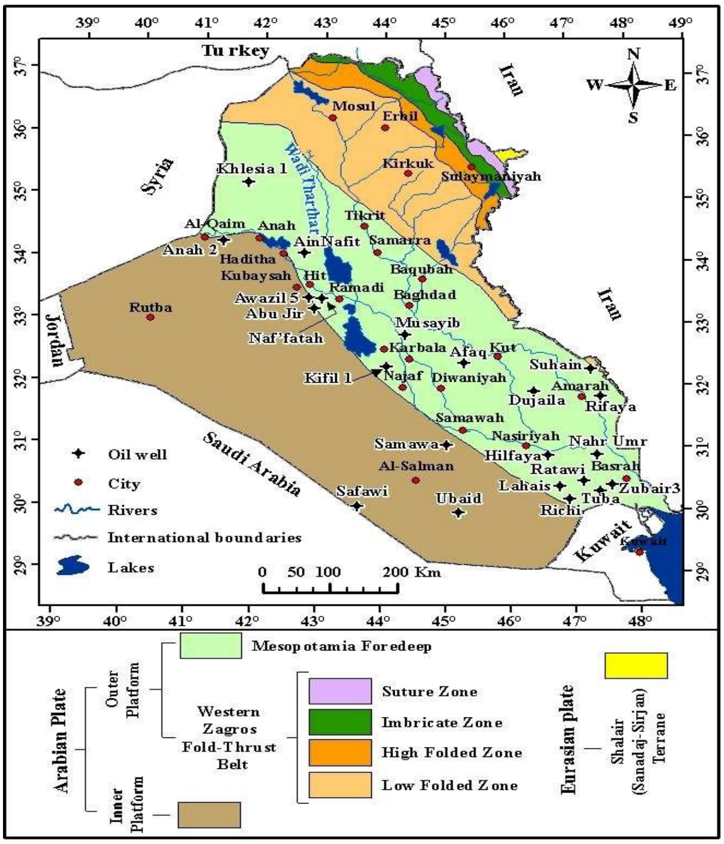

Figure 4. Tectonic divisions of Iraq [19].

2.2. *Field dynamic test and geo-seismic investigations*

The information from 59 borehole sources was used in this analysis to characterize the site completely. To ascertain the soil conditions and characteristics at the study site, a model drilling rig was used to drill holes with a depth range of 0.5 m to 25 m. SPT N-values for N_{60} were adjusted for field testing procedures at 60 % hammer efficiency and normalized at 1 % effective overburden pressure. The following steps were used to execute SPT in all boreholes. Split barrel samplers were used for this experiment. The sampler was driven into the ground at different depths by a 63.5 kg slide-hammer that fell freely from a height of 760 mm onto an anvil that was placed on surface of the drill rod. To advance the final 300 mm sampler, the number of blows required was mentioned. A good shear wave velocity profile is required to assess seismic site dependent parameters appropriately. Cross-hole and down-hole seismic methods are the most extensively employed for velocity logging nowadays. The dynamic properties of the underlying layers can also be determined via seismic refraction, which is widely employed.

The cross-hole and down/up-hole approaches both rely on monitoring body waves and yield reasonably accurate results. On the other hand, boreholes necessitate the drilling of one or more. Also in progress were down-hole seismic explorations at four locations. As seismic waves move through the surrounding rock and soil, the arrival times of compressional (P) and shear (S) waves will be recorded during borehole seismic surveys. To collect data for the down-hole test, a seismic source (hammer, wood, and steel plate) is set up on the surface near the hole, and the receiver is lowered into the hole and then raised with a 1-meter depth interval. The following is how the source is created:

A hammer striking a steel plate produces P-waves. There is a steel plate 1.25 meters from the borehole's centre. S-waves are created by hammering a piece of wood on both ends to create S-waves with polarity opposite each other. Fig. 5 shows that the wood is put 2.5 meters from the borehole's centre, as depicted. A 3D (xyz) pattern of three direction geophones makes up the receiver. S-wave and P-wave time arrivals are detected using two orthogonal horizontal geophones (x, y) and one vertical z. A clamping mechanism secures the tool to the borehole wall at each receiver level, ensuring good coupling between the wall and geophones and, as a result, reduced seismic noise. When conducting a down-hole survey, the raw data collected includes travel periods for P and S waves, distances from the source to the borehole, and receiver depths. The compression velocity of (Vp) and shear wave velocity (Vs) may be estimated using the measured time and measured distance. The Shear Modulus (G), Poisson's Ratio (ν), Mass Density (ρ) and Young's Modulus (E) could then be calculated using the Eq. (2, 3 and 4) below:

$$\text{Shear Modulus}: G = \rho V s^2; \tag{2}$$

$$\text{Poisson's Ratio}: \nu = \left(Vp^2 - 2Vs^2\right) / 2\left(Vp^2 - Vs^2\right); \tag{3}$$

$$\text{Young's Modulus}: E = 2G\left(1+\nu\right). \tag{4}$$

The seismic wave velocity test was conducted for four (4) downhole tests the project site. The downhole locations are 1, 2, 3, and 4 at location coordinates. Summary of test results is shown in Table 1.

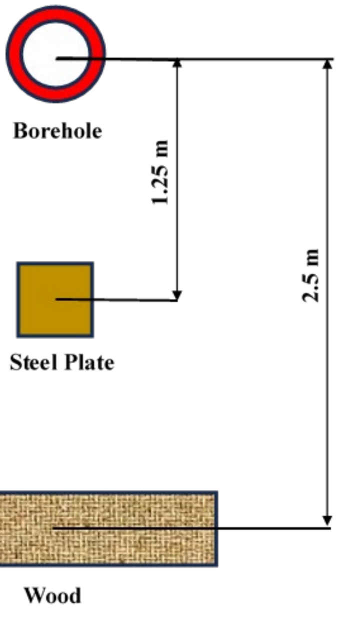

Figure 5. Express of Down-hole velocity test.

Table 1. Summary of results of Down-hole test.

Site NO.	Location Coordinates		L.L% average	P.I% average	N (average)	Undrained shear strength c_u (Average) kPa	Average Shear Wave Velocity ($\tilde{v}s$)
	E	N					
1	45.964396	31.354063	45	24	10	72.9	224.7
2	45.964746	31.353724	45.5	20.9	10	200.2	225.3
3	45.965898	31.354026	50.4	29.6	8	50	224.1
4	45.966386	31.354499	45	26	20	34	238.1

3. Results and Discussion

3.1. Suggested correlation between SPT N and shear wave velocity

This investigation developed correlations between Vs and SPT-N using 59 data points from borehole pairings. The N-SPT has to be corrected according to the following correction [21].

$$\dot{N}_{cor} = \dot{N}_{field} \cdot C_N \cdot \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_4.$$

where C_N adjustment for effective overburden correction computed as:

$$C_N = \left(\frac{95.76}{\dot{\sigma}_0} \right)^{0.5}$$

- $\dot{N}_{cor}$ is numbers of bowls corrected,
- η_4 is correction for Bore hole diameter,
- η_3 is correction for length of drill rods,
- η_2 is correction for length depends on the length,
- η_1 is correction for energy.

Correlations were derived from the current database using a simple regression analysis SPT-N adjusted values, and the measured values of Vs are given in Figure 6 as a scatter plot of points. For each SPT-N value, a correlation was applied to predict Vs. We calculated the R-squared value (R^2) and the root mean square deviation for each correlation based on the actual and expected Vs values (RMSD). This study proposed new connections between Vs and the soil's corrected SPT-N levels. The correlations are also presented in Fig. 6. Table 2 below provides a summary of the current, pertinent SPT-Vs that were chosen for study.

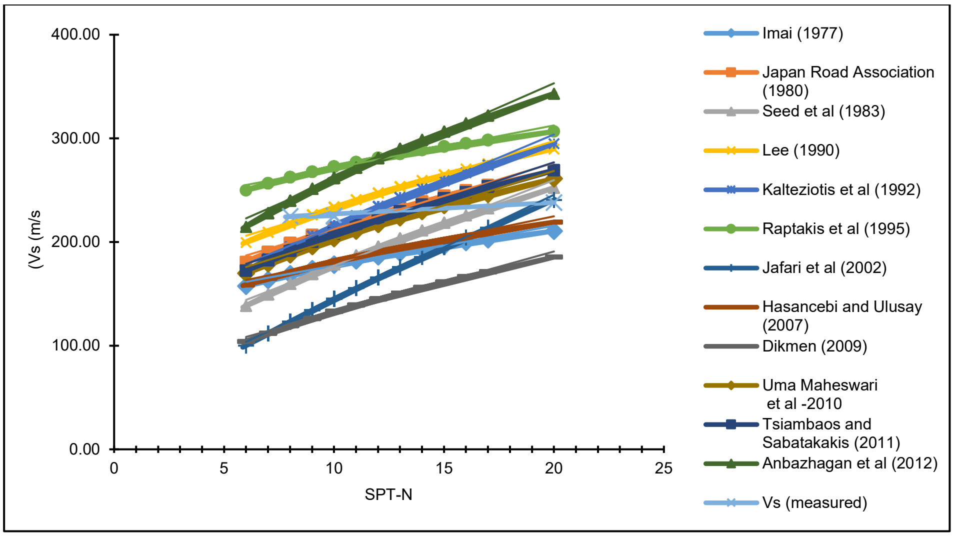

Figure 6. Correlation of VS and N-SPT for all locations.

Table 2. Summary of existing relevant SPT-Vs selected for evaluation.

Item No.	Authors	Original Equations	Remarks
		SPT-Vs Correlations	
1	Imai (1977) [22]	$Vs= 102N^{0.242}$	Developed for Cohesive-Soils based on geophysical tests for Vs
2	Japan Road Association (1980) [23]	$Vs=100 N^{0.33}$	Developed for Cohesive- Soils based on geophysical tests for Vs
3	Seed et al. (1983) [24]	$Vs= 56.4 N^{0.5}$	Developed for Cohesionless Soils based on geophysical tests for Vs
4	Lee (1990) [25]	$Vs=114.43 N^{0.31}$	Developed for Cohesive Soils – Vs from seismic downhole tests
5	Kalteziotis et al. (1992) [26]	$Vs= 76.6 N^{0.45}$	Developed for Cohesive-Soils using geophysical tests for Vs Soils
6	Raptakis et al. (1995) [27]	$Vs= 184.2 N^{0.17}$	Developed for Cohesive Soils using geophysical tests for Vs
7	Jafari et al. (2002) [4]	$Vs=27 N^{0.73}$	Developed for Cohesive Soils – Vs from seismic refraction, downhole and SASW
8	Hasancebi and Ulusay (2007) [5]	$Vs=97.89 N^{0.269}$	Developed for Cohesive Soils – Vs found from field Geoseismic tests
9	Dikmen (2009) [28]	$Vs= 44 N^{0.48}$	Developed for Cohesive-Soils – Vs determined from field Geoseismic tests
10	Uma Maheswari et al. (2010) [29]	$Vs= 89.31 N^{0.358}$	Developed for Cohesive-Soils – Vs determined from MASW
11	Tsiambaos and Sabatakakis (2011) [30]	$Vs= 88.8N^{0.370}$	Developed for Cohesive-Soils – Vs based on seismic cross hole tests
12	Anbazhagan et al. (2012) [31]	$Vs=106.63 N^{0.39}$	Developed for Cohesive-Soils – Modified previous correlations to suit indigenous setting

3.2. Data Analysis

Most process modelling applications rely on graphical residual analysis, a statistical tool used for model validation. The appropriateness of different model parts can be assessed using several sorts of plots of residuals from a fitted model. The (R^2) statistics and other numerical model validation methods are also valuable, but they are rarely as effective as graphical methods. It is easy to visualize a wide range of complex relationships between the model and data using graphic tools. In this way, the validity of the regression model is examined further by doing residual analysis. The residual graphs for each model are shown in Fig. 7. The residuals are horizontal, evenly dispersed, and random, demonstrating a satisfactory fit to the data by the regression model with equal variance from the horizontal axis. For the most part, the regressed data is well-suited to all of the regression equations' values. The normalized consistency ratio can assess how well the equations for predicting Vs value are performing. It is expressed in Eq. (5) as Normalized Consistency Ratio (Cd).

$$Cd = \left(V_{SM} - V_{SC}\right) / N_{(SPT)}. \tag{5}$$

V_{SC} is derived using correlation shear wave velocity models, and SPT-N is the SPT blow count corresponding to V_{SC}, whereas V_{SM} is derived from down-hole test Vs measurements. Fig. 7 compares V_{SM} and V_{SC} to assess the predictive strength of the correlations. The proposed correlations, with the exception of SPT-N values, appear to perform well in the prediction of Vs according to the figure, therefore the Cd value is close to zero.

To assess how well the various formulae performed in foretelling the shear wave velocity of the collected data, the Root Mean Square Error (RMSE) values of the proposed correlation were compared to the other formulas. Eq. (6) gives the RMSE values, where V_{SM} is derived from the Down-hole Test and derived from correlation shear wave velocity models, whereas Vsc is derived from SPT-N blow counts that correlate to V_{SC}, and where n is the number of measurements. As demonstrated in Table 3, the average shear waves with RMSE of 21.23 (m/Sec) had a lower error value than all of those provided by researchers.

$$RMSE = \sqrt{\sum_{i}^{n} \frac{V_{SC} - V_{SM}}{n}}. \tag{6}$$

Fig. 8 also shows comparisons between the measured Vs and the anticipated Vs from several models.

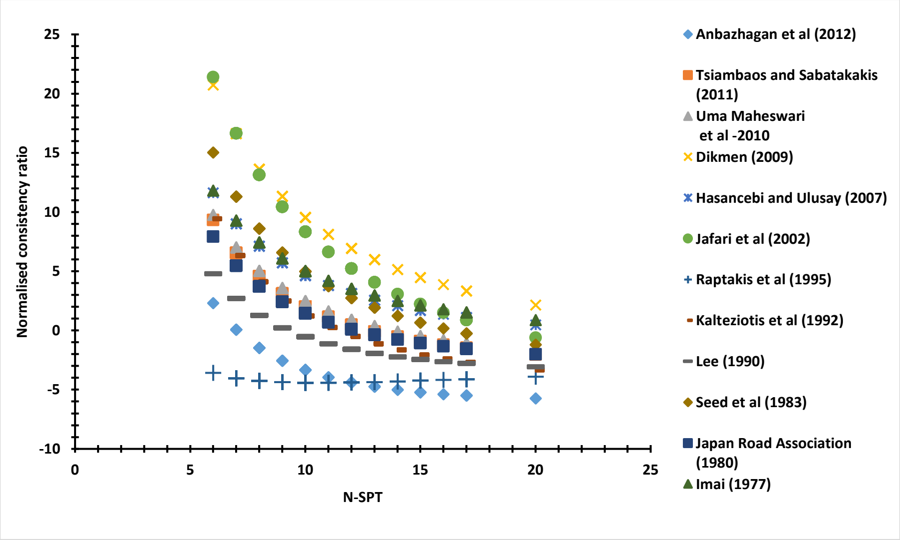

Figure 7. Normalized consistency ratio (Cd) calculated using corrected N values and correlation shear wave velocity Vs from different references.

Table 3. Comparison of the RMSE values of the studied correlations with measured average shear wave.

Item No.	Authors	Original Equations	RMSE (m/sec)	R^2
1	Imai (1977) [22]	$Vs= 102N^{0.242}$	48.11	0.9853
2	Japan Road Association (1980) [23]	$Vs=100\ N^{0.33}$	21.23	0.9885
3	Seed et al. (1983) [24]	$Vs= 56.4\ N^{0.5}$	48.67	0.9936
4	Lee (1990) [25]	$Vs=114.43\ N^{0.31}$	23.03	0.988
5	Kalteziotis et al (1992) [26]	$Vs= 76.6\ N^{0.45}$	27.44	0.9923
6	Raptakis et al (1995) [27]	$Vs= 184.2\ N^{0.17}$	49.49	0.9824
7	Jafari et al (2002) [4]	$Vs=27\ N^{0.73}$	78.74	0.9981
8	Hasancebi and Ulusay (2007) [5]	$Vs=97.89\ N^{0.269}$	44.40	0.9863
9	Dikmen (2009) [28]	$Vs= 44\ N^{0.48}$	91.32	0.9931
10	Uma Maheswari et al. (2010) [7]	$Vs= 89.31\ N^{0.358}$	27.25	0.9894
11	Tsiambaos and Sabatakakis (2011) [30]	$Vs= 88.8N^{0.370}$	25.21	0.9898
12	Anbazhagan et al. (2012) [32]	$Vs=106.63\ N^{0.39}$	51.04	0.9905

A specific correlation was created to account for the impact of the local SPT hammers utilized, workmanship, and geology. Statistical correlations between the two parameters were created using 63 data pairs between corrected SPT-N values and measured values of Vs. Because corrected SPT-N values have a significant impact on the estimation of Vs, they were used in the creation of this correlation. The models listed below were chosen to provide correlations between SPT-N and Vs for Eq. (7):

$$Vs = p \cdot N^{q}, \tag{7}$$

where N is corrected SPT-N and p, q are coefficients. The overburden effects and the SPT-N variance were taken into account by using this model. Fig. 8 makes it evident that the Vs changes practically linearly with N. Nonlinear regression was performed for the model using least squares analysis. The Equation 7 was developed as presented in Eq.(8):

$$Vs = 92.922 \cdot N^{0.3408}. \tag{8}$$

Table 4 provides an overview of the degree of fitness of various equations. Equation (8) produced the strongest correlation, with an R^2 of 0.9889 and an RMSD of 28.46, demonstrating the highest ability to forecast. It is suggested that this equation be used because of its high fitness level for the dataset.

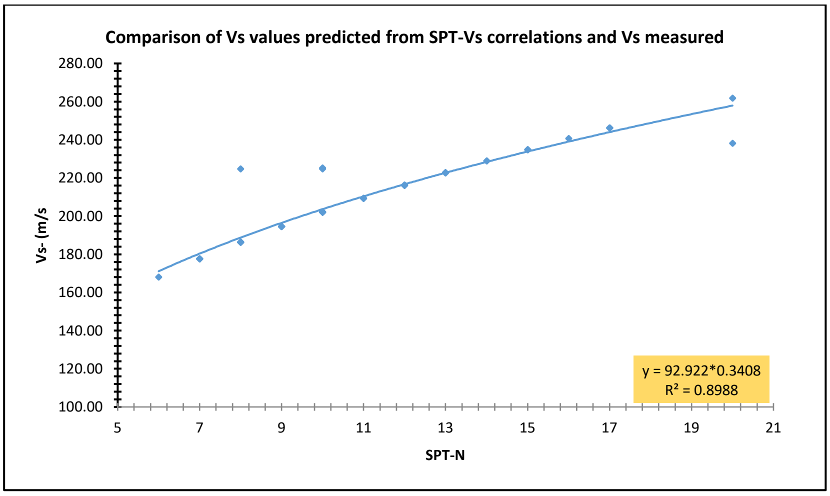

Figure 8. Comparisons between Proposed and measured Vs and SPT-N Correlations.

Table 4. The degree of fitness of various equations.

Correlation for Vs (m/s)	RMSD	R^2
$Vs = 92.922\ N^{0.3408}$	28.46	0.9889

4. Conclusions

The study used the data from 59 borehole locations in the city of Al-Nasiriya where dynamic field SPT tests were carried out and used to complete the full field testing. After conducting necessary data analyses, SPT tests close to the down-hole test locations were chosen to create correlations between SPT-N and Vs. The required data were analyzed using linear models and correlation coefficients (R^2) were determined. R^2 and error values for the power model were high, indicating that this model provides the best fitting relationship between the Vs and SPT-N parameters. The following conclusions were obtained:

1. Regression analysis yielded correlations between the adjusted N-values and Vs for all equations (with a power model). The high correlation coefficient for all of the produced correlations reveals a strong association between these two soil parameters (SPT N and Vs), indicating that these proposed correlations can be used to estimate the Vs value of this location acceptably.
2. Compared to other equations, the proposed formula had a lower RMSE value of 21.23 and performed better at predicting Vs values. The dataset is best fit by the empirical correlations presented in this study.

Finally, GIS is an important tool for geotechnical engineering, including preliminary site investigations. On the GIS-based map that displays average shear wave velocity (Vs) and average value N in Al-Nasiriya city, the corrected average SPT-N values and average shear wave velocity (Vs) for all locations of the study area are readily visible. The GIS-based maps created in this study can be useful to foundation designers during the initial site selection and preliminary design of the project in both static and seismic conditions.

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