Investigation of the Correlation between SPT Number, Shear Wave Velocity, and Small-Strain Shear Modulus in Northern Iran

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ABSTRACT

The shear wave velocity (V_S) and the small-strain shear modulus (G_{max}) are crucial parameters to assess the dynamic properties of soil and the seismic characteristics of a site. In field trials, it may be challenging and costly to quantify these factors, limiting their feasibility. Thus, it is essential to determine indirectly V_S and G_{max} using empirical equations linked to the SPT number. The present research focused on the seismic zone in the northern regions of Iran, where construction is rapidly increasing. The field tests were conducted by drilling eleven boreholes and analysing the correlation between SPT number, shear wave velocity, and small-strain shear modulus in clayey, sandy, and silty soil. The results were validated using data from three boreholes in a different area of northern Iran. G_{max} is a parameter that reflects the dynamic characteristic of soils, specifically the hardness of geomaterials under shear deformation. Variations in the specific weight of soil layers affecting the small-strain shear modulus were analysed by correlating the SPT number to the small-strain shear modulus. The research findings demonstrated a strong correlation between the SPT number, shear wave velocity, and small-strain shear modulus. Previous studies and data validation verified the models proposed in this research. Clayey soils are more sensitive to changes in the specific weight of each layer than sandy and silty soils. Since this sensitivity exhibits a non-linear relationship, it is crucial to consider the specific weight of each layer of soil when determining correlations for clayey soils.

KEYWORDS

Seismic Waves; Standard Penetration Test; Downhole Test; Small-Strain Shear Modulus; North of Iran

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1. Introduction

Seismic wave velocity and small-strain shear modulus are critical parameters in civil engineering, particularly for seismic analysis of structures [1,2]. Due to the high cost and complexity of geophysical tests, researchers have sought correlations between these parameters and simpler field tests, such as the Standard Penetration Test (SPT). The SPT, a widely used geotechnical test, helps estimate soil properties. Moreover, numerous empirical relationships (often in power-law forms, such as V_S = XNY) have been proposed to link SPT values (N) to shear wave velocity (V_S). These correlations vary significantly across soil types (clay, sand, silt), with coefficients X and Y reflecting regional soil characteristics. For instance, in clays, X ranges from 27 to 132 and Y from 0.23 to 0.73, while sands show even broader variations [3-5].

The small-strain shear modulus (G_{max}) is vital for geotechnical design under static and dynamic loads. While traditionally measured via geophysical or laboratory tests (e.g., resonant column), in recent studies, Gmax was correlated with SPT-N values for a cost-effective estimation. These correlations differ by soil type and region, emphasising the need for site-specific calibration. For example, lateritic and saprolitic soils display distinct behaviors, requiring separate formulas. Studies also highlight the influence of factors like hammer energy, fines content, and depth on SPT-based predictions, with corrected N-values often improving accuracy [6, 7].

The present study focuses on northern Iran's Caspian Sea region, where rapid construction demands reliable local correlations. By conducting SPT and downhole seismic tests across 11 boreholes, the authors derived new region-specific relationships between SPT-N, V_S, and GmaxGmax, accounting for layer-specific density variations. In the research, modelling precision was enhanced by isolating density effects on G_{max} for clay, sand, and silt layers. These findings provide tailored correlations for seismic microzonation and geotechnical projects in the area, addressing gaps in previous generalised models.

2. Methodology

In this study, correlations were developed between SPT blow counts (N), shear wave velocity (V_S), and small-strain shear modulus (G_{max}) using regression analysis, where Gmax was calculated through the fundamental relationship $G_{max} = \rho V_S^2$ with ρ representing soil density. Field and laboratory data were processed to minimize scatter and categorised into clay, silt, and sand groups. In the research, a power-law relationship was employed between SPT-N and Vs, establishing site-specific correlations for the soils of northern Iran while examining the effects of density on Gmax. Model accuracy was quantified using the root mean square error metric RMSE = $\sqrt{(1/n \sum(yi-\hat{y}i)^2)}$, where yi and ŷi represent measured and predicted values, respectively.

The investigation focused on Rasht city in Gilan Province, where eleven boreholes were drilled to depths of 30 m in sedimentary soils with high groundwater tables. Standard penetration tests were conducted at 2-meter intervals following ASTM procedures, using a standard hammer drop system. Downhole seismic testing measured wave velocities for V_S determination, which was subsequently used in the $G_{max} = \rho V_S^2$ equation. Comprehensive field testing included both SPT and downhole seismic measurements, conducted following strict quality control protocols. PVC-cased boreholes enabled precise wave velocity measurements at 1-meter increments, with the resulting VS values fed into the Gmax calculation. To validate the proposed relationships, data from three additional boreholes located in Mazandaran Province, in the northern region of Iran, were utilized.

3. Discussion and results

The data for clayey, silty, and sandy soils were selected to determine the correlation between V_S and G_{max} with SPT-N values. Most data for all three soil types fell within ±1 STD. For clay (Vs: 150–523 m/s), STD was 94 m/s; for sand (Vs: 220–411 m/s), STD was 72 m/s; and for silt (Vs: 135–565 m/s), STD was 126 m/s. Over 95% of the data points for each soil type lie within ±1 STD, with only six clayey data points (two CH, four CL) near the −1 STD boundary. Table 1 presents the correlation equations between Vs and SPT-N for northern Iran, including R^2 and RMSE values. For clay, the equation * V_S = 19.31N^0.75* (R^2 = 0.82, RMSE = 40.62) shows strong agreement. Sandy soils follow * V_S = 33.30N^0.67* (R^2 = 0.95, RMSE = 41.15), while silty soils fit * V_S = 16.86N^0.78* (R^2 = 0.83, RMSE = 50.57). All data points within ±0.2 of the equality line, confirm the models' accuracy.

Table 1. The correlation between shear wave velocity and SPT (N-value) in Northern Iran

Type of soil	Formula	R^2	RMSE
Clay	$V_S = 19.31N^{0.75}$	0.82	62.40
Sand	$V_S = 33.30N^{0.67}$	0.95	15.41
Silt	$V_S = 16.86N^{0.78}$	0.83	57.50

Figure 1 compares the derived correlations with prior studies. For clay (SPT-N: 13–34), the proposed equation aligns closely with that of Dickmann and Dégé et al., showing a deviation of ≤12%. Sandy soils (SPT-N: 18–41) exhibit ≤10% deviation from Seed et al., while silty soils (SPT-N: 10–38) demonstrate lower V_S predictions for SPT-N < 18 but converge with existing studies at higher SPT-N values. These discrepancies arise from sampling methods and geological conditions, underscoring the need for soil-specific correlations.

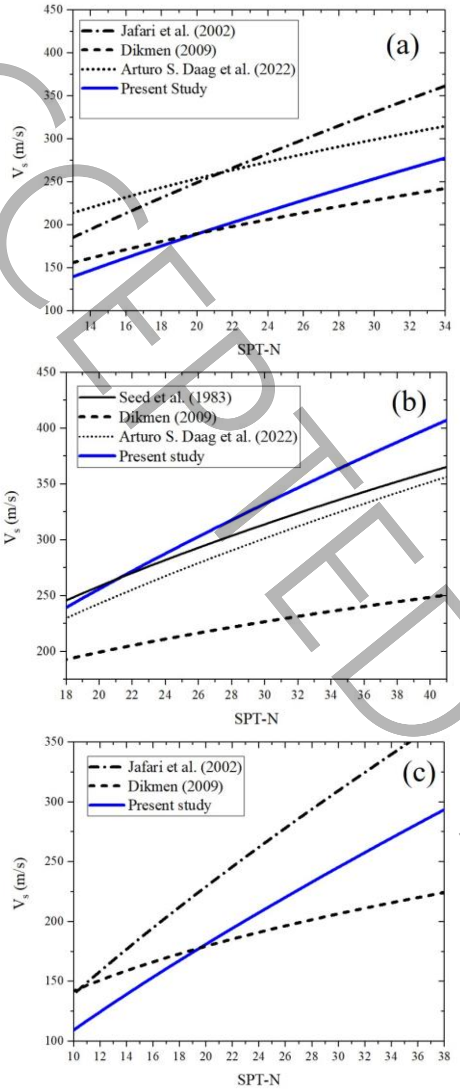

Figure 1. The comparison of derived SPT-N vs. V_S correlations with previous studies for: (a) clay, (b) sand, and (c) silt

Table 2 lists G_{max} -SPT-N correlations. The results demonstrated that unit weight (ρ) significantly influenced G_{max}. For clay, a nonlinear relationship, ρ = 1.59N^0.26, was observed, indicating the need for layer-specific ρ values. In contrast, sand exhibited nearly linear behavior (ρ ≈ 1.79), while silt followed the trend ρ = 1.43N^0.18.

Table 2. The correlations between small-strain shear modulus (G_{max}) and SPT N-values for clayey, sandy, and silty Soils in Northern Iran

Type of soil	Formula	R^2	RMSE
Clay	$G_{max}=0.59N^{1.76}$	0.91	46.24
Sand	$G_{max}=1.97N^{1.37}$	0.96	57.14
Silt	$G_{max}=0.40N^{1.74}$	0.90	15.50

Figure 2 illustrates normalized G_{max} /ρ (linear trend) and G_{max} vs. SPT-N (nonlinear trend). Clay displays steeper slopes, highlighting the influence of ρ, whereas sand and silt show minimal variation. This confirms that ρ must be explicitly considered for clay, although it can be averaged for sand/silt. The study highlights the significance of soil-specific models in dynamic parameter estimation, as validated by three boreholes in Mazandaran, where predictions fell within ±15% of the measured values.

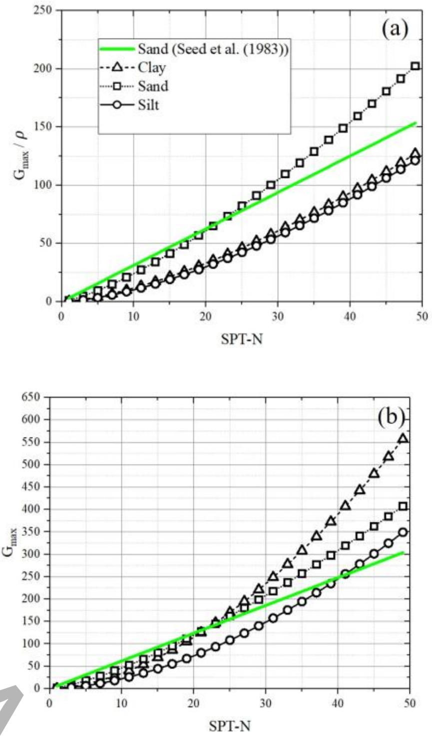

Figure 2. Investigating the effect of unit weight variations on small-strain shear modulus (G_{max}) for three soil types (clay, sand, silt): (a) Normalized G_{max} vs. unit weight to SPT-N ratio and (b) G_{max} vs. SPT-N Variations

4. Conclusions

This study established novel empirical correlations between SPT-N values and shear wave velocity (V_S) as well as the small-strain shear modulus (G_{max}) for clayey, sandy, and silty soils in northern Iran, based on extensive field testing across eleven locations in Rasht, along with validation with three independent boreholes in Mazandaran. The results demonstrate distinct ranges for each soil type: clayey soils (V_S = 150–523 m/s, G_{max}= 30–287 MPa), sandy soils (V_S= 135–565 m/s, G_{max}= 24–232 MPa), and silty soils (V_S= 220–411 m/s, G_{max}= 90–354 MPa). A consistent positive trend was observed, with V_S and G_{max} increasing alongside higher SPT-N values for all soil types. Notably, clayey soils revealed greater sensitivity to density variations compared to sandy and silty soils. These correlations offer a practical, cost-effective alternative to geophysical testing, enabling reliable seismic site characterization using widely available SPT-N data, which is particularly valuable for preliminary assessments in similar geotechnical contexts.

5. References

[1] H. Haghsheno, M. Arabani, Seismic Bearing Capacity of Shallow Foundations Placed on an Anisotropic and Nonhomogeneous Inclined Ground, Indian Geotechnical Journal, 51(6) (2021) 1319-1337.

[2] M. Veiskarami, R. Jamshidi Chenari, M.A. Ahmadi, M.H. Hatefi, A Study on the Seismic Passive Earth Pressure on Rigid Retaining Walls Considering Seismic Acceleration Field, Journal of Earthquake Engineering, 27(8) (2023) 2013-2033.

[3] M.K. Jafari, A. Shafiei, A. Razmkhah, Dynamic properties of fine grained soils in south of Tehran, (2002).

[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] A.S. Daag, O.P.C. Halasan, A.A.T. Magnaye, R.N. Grutas, R.U. Solidum Jr, Empirical correlation between standard penetration resistance (SPT-N) and Shear Wave Velocity (Vs) for soils in Metro Manila, Philippines, Applied Sciences, 12(16) (2022) 8067.

[6] H.B. Seed, I.M. Idriss, I. Arango, Evaluation of liquefaction potential using field performance data, Journal of geotechnical engineering, 109(3) (1983) 458-482.

[7] H.B. Seed, I.M. Idriss, I. Arango, Evaluation of liquefaction potential using field performance data, Journal of geotechnical engineering, 109(3) (1983) 458-482.