Modern correlation for SPT-*N* and V_s to predict the in-situ D_r based on geotechnical parameters of cohesionless soils

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ABSTRACT
In the past few decades, a variety of formulae correlating the shear wave velocity (V_s) to the energy corrected standard penetration blow counts (N_{60}) for sandy soils in a power-law form ($V_s = a.N^b$) were developed. The applicability of these correlations on different soils was highly questioned by many researchers and in the industry as well. This paper presents a detailed study on 25 common different correlations from literature. Almost all examined correlations have discrepancies and high trend deviations due to the variation of the geological conditions of their based-tested sands and/or combining results from different sites. An investigation was performed on the utilized *a* and *b* mathematical factors that helped to find an explanation of the discrepancies. In addition, a modern correlation is proposed based on recent technologies of evaluating the soil geotechnical parameters. Such correlation is able to plot multiple trends that accurately meet the trend of all examined literature formulae at a single point representing the in-situ relative density (D_r) encountered at each site and stated in the literature studies. Eventually, an application for estimating the in-situ relative density is presented.

RÉSUMÉ
Au cours des dernières décennies, diverses formules corrélant la vitesse de l'onde de cisaillement (V_s) au nombre de coups de pénétration standard corrigé en énergie (N_{60}) pour les sols sableux en forme de $V_s = a.N^b$ ont été développées. L'applicabilité de ces corrélations sur différents sols a été fortement remise en question par de nombreux chercheurs et dans l'industrie également. Cet article présente une étude détaillée sur 25 corrélations différentes communes de la littérature. Presque toutes les corrélations examinées présentent des écarts de tendance élevés en raison de la variation des conditions géologiques de leurs sables testés ou de la combinaison des résultats de différents sites. Une enquête a été réalisée sur les facteurs mathématiques *a* et *b* utilisés qui ont aidé à trouver une explication des écarts. De plus, une corrélation moderne est proposée basée sur des techniques récentes d'évaluation des paramètres géotechniques du sol. Une telle corrélation est capable de tracer plusieurs tendances qui correspondent avec précision à la tendance de toutes les formules de la littérature examinées en un seul point représentant l'indice de densité (Dr) rencontré sur chaque site et indiqué dans les études de la littérature. Enfin, une application pour estimer l'indice de densité est présentée.

1 INTRODUCTION

The Standard Penetration Test, SPT, is widely used in the industry for field investigations of sandy soils due to test simplicity in terms of equipment and procedures in addition to the capability of extracting disturbed soil samples. This type of test is usually used to estimate the static strength parameters of the soil. However, determination of the dynamic parameters of sands is crucial when liquefaction potentials are expected. Therefore, many researchers (e.g., Anbazhagan et al., 2012 & 2013 and Hussien and Karray, 2015) were interested in presenting simplified correlations of the shear wave velocity, V_s, for the dynamic evaluations with the SPT blow counts, *N*.

1.1 Basic State of Knowledge

Considerable interest in correlating V_s to SPT-*N* was observed in the last few decades. Researchers, such as Valverde et al., 2014; Anbazhagan et al., 2013; Akin et al., 2011; Sykora and Stokoe, 1983; and Seed et al., 1983 followed the pioneering ideas of Kanai, 1966, to present V_s as a direct correlation of SPT-*N* in a power-law form ($V_s = a.N^b$). Where *a* and *b* are constants usually estimated by statistical regression analysis on the experimented data set. Table 1 summarizes examples of these literature relationships for sandy soils.

Figure 1 illustrates that these correlations show remarkable deviations in trend. In other words, at a given SPT-N_{60} value, almost all correlations predict different values of V_s. For example, for loose to compact sands of $N_{60} \approx 10$, the predicted V_s values range was 150 – 250 (m/sec). Also, for compact to dense sands of $N_{60} \approx 30$, V_s values range was 225 – 400 (m/sec), similarly, for dense to very dense sands of $N_{60} \approx 50$, V_s values range was 250 – 540 (m/sec). In summary, these common correlations that widely used in the geotechnical domain have deviations in results up to approximately 216%.

The primary purpose of the current study is to investigate the implicit factors which may cause divergences in trends. The Authors suggest that physical properties such as; mean particle size, D_{50}, the coefficient of uniformity, C_u, the two-dimensional angularity of particles, A_{2D}, and the void ratio range, e_{max}-e_{min}, have significant influences on the technical properties of sand consequently contributing to the above-illustrated deviations (e.g., Lashin et al., 2021 and Ghali et al., 2018, 2020a & 2020b).

Table 1. Literature correlations of Vs with SPT-N

Reference	Type of soil	correlation
Kanai, 1966	Sandy soils	$V_s = 18.9N^{0.60}$
Shibata, 1970	Sandy soils	$V_s = 31.7N^{0.54}$
Ohta et al., 1972	Sands	$V_s = 87.2N^{0.36}$
Ohsaki and Iwasaki, 1973	Sandy soils	$V_s = 59.0N^{0.47}$
Imai, 1977, 1981 & 1982	Sands	$V_s = 80.6N^{0.331}$
Ohta and Goto, 1978	All soils	$V_s = 85.35N^{0.348}$
Seed and Idriss, 1981	All soils	$V_s = 61.0N^{0.50}$
Seed et al., 1983	Sands	$V_s = 56.4N^{0.50}$
Sykora and Stokoe, 1983	Sands	$V_s = 100.5N^{0.29}$
Okamoto et al., 1989	Sands	$V_s = 125N^{0.30}$
Lee, 1990	Sands	$V_s = 57.4N^{0.49}$
Raptakis et al., 1995	Sands	$V_s = 100N^{0.24}$
Rollins et al., 1998	Holocene gravel	$V_s = 63N_{60}^{0.43}$
Pitilakis et al., 1999	Sands	$V_s = 145N_{60}^{0.178}$
Wride et al., 2000	Sands	$V_{s1} = a(N_1)_{60}^{0.25}$
Andrus et al., 2004	0.16 < D_{50} < 0.25	$V_{s1-cs} = 87.8(N_1)_{60-cs}^{0.253}$
Hasancebi and Ulusay, 2007	Sands	$V_s = 131N_{60}^{0.205}$
Hanumantharao and Ramana, 2008	Sands	$V_s = 79N^{0.434}$
Dikmen, 2009	Sands	$V_s = 73N^{0.33}$
Uma Maheswari et al., 2010	Sands	$V_s = 100.53N^{0.265}$
Akin et al., 2011	Sands	$V_s = 38.55D^{0.481}N^{0.176}$
Akin et al., 2011	Alluvial sands	$V_s = 52.04D^{0.177}N^{0.359}$
Anbazhagan et al., 2013	Pliocene sands	$V_s = 60.17N^{0.56}$
Fauzi et al., 2014	Sands	$V_s = 105.03N^{0.286}$
Naik et al., 2014	All soils	$V_s = 73.53N_{60}^{0.40}$

V_s, V_{s1} & $V_{s1\text{-}cs}$ are in m/sec, *D50* is in mm, *D* is the depth below grade surface in m, $(N_1)_{60}$ is the stress-normalized energy-corrected SPT blow counts, V_{s1} is the stress-normalized shear wave velocity, and $V_{s1\text{-}cs}$ is the stress-normalized shear wave velocity for clean sands.

2 DISCUSSION ON LITERATURE WORKS

In order to study the wide variation in all V_s~N correlations stated in Table 1, the exponent factor *b* was plotted against the amplitude factor *a* as shown in Figure 2. A negative relationship trend can be observed between the plotted *a* & *b* values. Trend divergencies were only observed in the stress normalized correlations (e.g., Wride et al., 2000) and the uncorrected SPT-N correlations. For instance, the correlations presented by Kanai, 1966, and Shibata, 1970, did not consider some SPT correction factors for hammer type, energy loss, rod length, and sampler inner diameter.

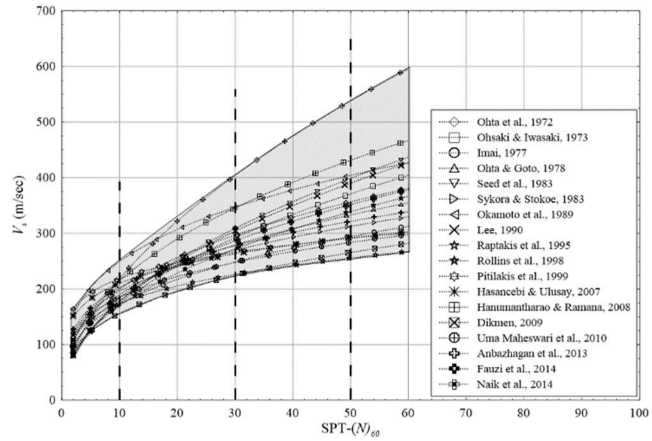

Figure 1. Comparison between literature correlations

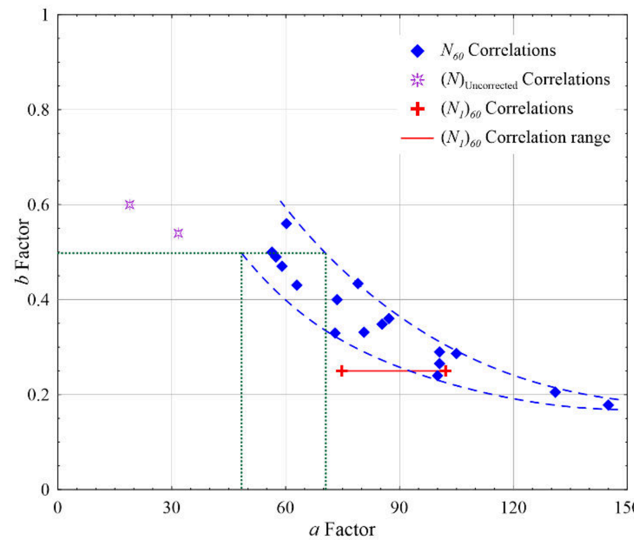

Figure 2. The exponent *b* against the amplitude *a*

From the negative trend range shown in Figure 2, it can be concluded that both *a* and *b* factors are just mathematical representations that somehow related considerably to each other. In other words, the same V_s~N correlation in a power-law form ($V_s = a.N^b$) can be represented by any given *a* value considering the corresponding *b* value. As shown in the following section, the authors suggest that both *a* and *b* values vary according to the soil's physical parameters (e.g., D_{50}, C_u, A_{2D} & e_{max}-e_{min}).

The trend range also shows that for a given *b* value there is a range of corresponding *a* values. This observation coincides with the literature. For example, Wride et al., 2000, when studied the CANLEX project used an exponent factor (*b*) of 0.25 and presented the corresponding amplitude (*a* values) to be in the range of (74.8 - 102.1) for the different tested sands. Similarly, Seed and Idriss, 1981 and Seed et al., 1983 utilized *b* = 0.50 and *a* factor varied from 56.4 to 61.0 for different soil gradations. As shown in Figure 2 and Section 4 of this article, the authors suggest that at *b* = 0.5, the amplitude could be in the approximate range of (48 - 71) that varies with D_{50}, A_{2D}, e_{max}-e_{min} & D_r.

3 V_{S1} ~ $(N_1)_{60}$ PROPOSED CORRELATIONS

Ghali et al., 2018 & 2020b, correlated $(N_1)_{60}$ to D_r and summarized their extensive study on the implicit effect of the physical parameters of unaged, uncemented, normally consolidated, clean sands, as:

$$(N_1)_{60} = 140\, exp^{-\frac{A_{2D}}{500}} D_{50}^{0.22}\, C_u^{0.5} D_r^2 \quad [1]$$

Where D_{50} is in mm. Ghali et al., 2020b, also pointed out that a maximum value of C_u = 8 should be used in Equation 1 for well-graded clean sands having a uniformity coefficient of more than 8. It should be noted that the aforementioned relation overestimates the SPT-*N* values for sands having fines content of more than 5%.

On the other hand, Ghali et al., 2018, presented V_{s1} as a function of the relative density and the technical parameters of clean sands as:

$$V_{S1} = 171.7\, exp^{-1.131(e_{max}-e_{min})-\frac{A_{2D}}{2000}} D_{50}^{0.061}\, C_u^{0.252}(D_r + 1.55) \quad [2]$$

Where D_{50} is in mm, and V_{s1} is in m/sec. Similar to Equation 1, a maximum value of C_u = 8 should be utilized in Equation 2 for all well-graded sands having $C_u \geq 8$ as they do not show a significant change in trend.

By isolating the *Dr* from Equation 1 and substituting it in Equation 2, the following formula can be obtained:

$$V_{s1} = \alpha_1 (N_1)_{60}^{0.50} + \alpha_2 \quad [3a]$$

where

$$\alpha_1 = 14.511\, exp^{\frac{A_{2D}}{2000}-1.131(e_{max}-e_{min})}\, D_{50}^{-0.049} \quad [3b]$$

and

$$\alpha_2 = 266.135\, exp^{-1.131(e_{max}-e_{min})-\frac{A_{2D}}{2000}} D_{50}^{0.061}\, C_u^{0.252} \quad [3c]$$

Where D_{50} is in mm, V_{s1} is in m/sec and Similar to Equations 1 & 2, a maximum value of C_u = 8 should be utilized in Equation 3 for all well-graded sands having $C_u \geq$ 8 as there are no significant changes in trend.

4 PREDICTING THE IN-SITU D_r FROM V_S AND $(N)_{60}$ MEASUREMENTS

Equation 3a presented the relationship between the stress normalized shear wave velocity and the stress normalized SPT-N. The standard penetration blow counts are widely normalized in accord with Equation 4 (e.g., Skempton, 1986 & 1987; Kulhawy and Mayne, 1990; Cubrinovski and Ishihara, 1999 & 2000; Daniel et al., 2003a & 2003b; Ghali et al., 2018). Also, V_{s1} values are routinely evaluated using Equation 5 (e.g., Robertson et al., 1992; Youd et al. 2001; Karray et al. 2011; Hussien and Karray 2015, Ghali et al., 2020a).

$$N_1 = N \left(\frac{P_a}{\sigma'_v}\right)^{0.50} \quad [4]$$

and

$$V_{s1} = V_s \left(\frac{P_a}{\sigma'_v}\right)^{0.25} \quad [5]$$

Where, P_a is a reference atmospheric pressure of 100 kPa; σ'_v is the effective overburden stress in same unit of *Pa*, and V_{s1} & V_s are in the same unit (e.g., m/sec).

Equations 4 and 5 show that in order to eliminate the P_a and σ'_v effects, V_{s1} should be directly proportion with $N_1^{0.5}$ that coincide with Equation 3a. Therefore, another attempt for predicting a generalized V_s~N_{60} correlation in the form of $V_s = aN^{0.5}$ is conducted as shown in Equation 6a. The superiority of utilizing an exponent factor b = 0.5 is not only including the D_r into the relation but also it automatically removes the stress normalization factors, stated in Equations 4 & 5. In details, Equation 2 was divided by the square root of Equation 1, then, the substitution of Equations 4 & 5 refers to an elimination of the stress normalization factors. The resulted relation for unaged, uncemented, normally consolidated, clean sands, with the development of D_r is:

$$V_s = a(N)_{60}^{0.50} \quad [6a]$$

where

$$a = 14.511\, exp^{\frac{A_{2D}}{2000}-1.131(e_{max}-e_{min})}\, D_{50}^{-0.049} \left(\frac{D_r+1.55}{D_r}\right) \quad [6b]$$

where, D_{50} is in mm, and V_s is in m/sec.

5 VERIFICATION STUDIES

Extensive database gathered by Ghali et al., 2018, from highly reputed publications (e.g., Liao et al., 2011, 2008 & 2007; Andrus et al., 2009 & 2004; Mayne, 2006) in addition to the CANLEX project after Robertson et al., 2000, was investigated to verify the applicability of the current proposals. The sands tested were from eleven sites in the United States, six sites in Japan, six sites in Canada, and one site each in Italy, Norway, and China. The predicted versus corrected $V_{s1\text{-}cs}$ values are presented in Figure 3 while the predicted versus estimated D_r values are presented in Figure 4.

The comparison in Figure 3 shows that Equation 3 is highly able to predict the stress-normalized shear wave velocity from the obtained field results of the energy-corrected standard penetration blow counts. The compared predicted V_{s1} values show an approximate deviation of 20 % from the measures in-situ stress-normalized shear wave velocity.

Similarly, the comparison in Figure 4 illustrates that Equation 6 can predict the in-situ relative density from the standard penetration testing results and a direct measurement of the shear wave velocity. The predicted D_r values from Equation 6 were compared to the stated values in the gathered literature and were found to have an average deviation of less than 20 %.

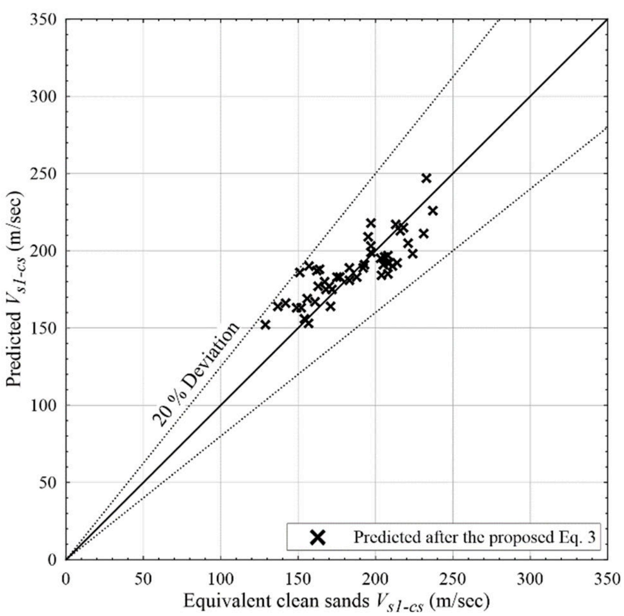

Figure 3. Comparative case study on Corrected $V_{s1\text{-}cs}$ database from literature with the predicted values of Equation 3.

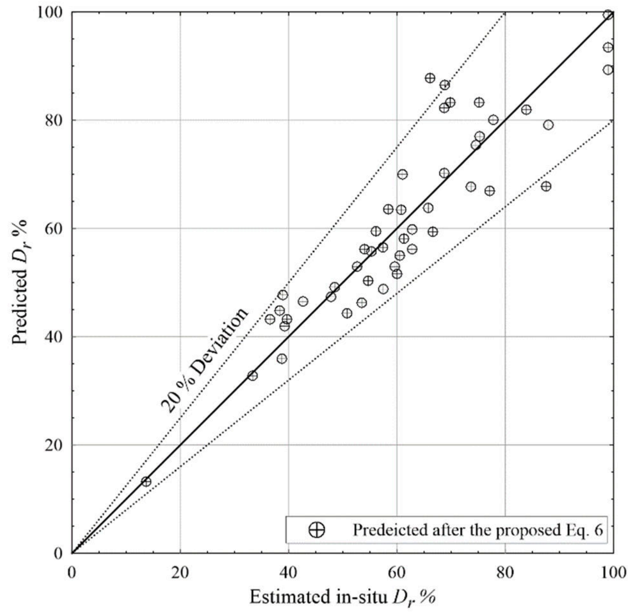

Figure 4. Comparative case study on estimated in-situ D_r database from literature with the predicted values of Equation 6.

6 SUMMARY AND CONCLUSION

A comparative investigation has been carried out on the 25 relations presented in Table 1, which are correlating SPT-N to V_s presented in a power-law form ($V_s = a.N^b$). The investigation shows that for the corrected N_{60} formulae, the amplitude factor, a, and the exponent factor, b, are related to each other by a negative relationship. However, most of the studied correlations have remarkable deviations in trend slope and interception. The authors suggest the reasons of such divergences to be:

- Some literature relations are only developed based on results of one type of sand and may not be applicable for another sand deposit of different physical parameters or relative density (e.g., CANLEX project). In this case, the factors *a* or *b* may vary for each sand.
- Other literature relations are developed by combining results for two or more different sands of different physical characteristics and under different DR values as well. that may lead to huge variations in slope for these relations.

Therefore, this paper presented a unified approach correlating SPT-N to V_s for individual sands based on the development of D_r considering the physical characteristics of the sand deposit.

The development of D_r controls the development of proposed SPT-N~V_s relation. While, the physical parameters of the clean sands, particularly, D_{50}, C_u, A_{2D} & e_{max}-e_{min} affect the trend performance by shifting or changing the slope of the SPT-N~Vs relation.

The present study was carried out on clean sand and granular materials. Therefore, the developed correlations may only be considered applicable for uncemented, young, clean sands. Additionally, the two-dimensional angularity was found to be sufficient to represent particle form size, as well as particle corner conditions, but does not take into consideration the surface roughness of coarse-grained particles (Ghali et al., 2018). Also, the effects of the presence of water or fines content was not included in this study.

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