Gilder, C., Vardanega, P. J., Pokhrel, R., De Risi, R., & De Luca, F. (2021). Assessing Transformation Models Using a Geo-Database of Site Investigation Data for the Kathmandu Valley, Nepal. In M. Barla, A. Di Donna, & D. Sterpi (Eds.), *Challenges and Innovations in Geomechanics - Proceedings of the 16th International Conference of IACMAG - Volume 1: IACMAG 2021* (pp. 331–338). (Lecture Notes in Civil Engineering; Vol. 125). Springer, Cham. https://doi.org/10.1007/978-3-030-64514-4_29

Peer reviewed version

Link to published version (if available):
10.1007/978-3-030-64514-4_29

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Assessing transformation models using a geo-database of site investigation data for the Kathmandu Valley, Nepal

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Abstract: The Seismic Safety and Resilience of Schools in Nepal (SAFER) project has an important aim of producing improved tools for geotechnical and earthquake engineers to assess seismic hazard in the Kathmandu Valley, Nepal. Geo-databases have the potential to offer geotechnical practitioners means to improve a-priori predictions of important soil parameters in geotechnical design. In this paper, some recent work to develop a new database of geotechnical information (SAFER/GEO-591) including shear wave velocity measurements is reported. Attempts to develop new transformation models to better predict shear wave velocity from more basic parameters such as SPT-N values are presented. Use of kriging to better map shear wave velocity for the study area is recommended as a suitable alternative to the presented correlations.

Keywords: Database, Transformation models, Site investigation, Kathmandu Valley

1 Introduction

Assessments of geotechnical variability in areas where data are too few to complete meaningful statistical analysis are often done by consulting published guidance (Phoon and Kulhawy, 1999a). Information on measures of geotechnical variability from past studies is often characterised by uncertainties resulting from both the inherent nature of the soil body, as well as measurement, statistical and model uncertainties (Phoon and Kulhawy, 1999a). This paper presents a case study of assessment of geotechnical variability in the data scare region of the Kathmandu Valley in Nepal. The work presented in this paper follows the building of the database SAFER/GEO-591 (Gilder et al., 2019b; Gilder et al., 2020). Efforts to deal with data scarcity range from standard measures of geotechnical variability including development of transformation models (e.g. Kulhawy and Mayne, 1990; Phoon and Kulhawy, 1999a; Phoon and Kulhawy, 1999b) to Bayesian approaches (e.g. Marache et al., 2009; De Risi et al., 2019).

2 Soil variability in the Kathmandu Valley, Nepal

SAFER/GEO-591 (Gilder et al., 2019b) was compiled using data from the literature, consultancy reports and data from groundwater well logs in the Kathmandu Valley, Nepal (Gilder et al., 2020) as well as some new investigations undertaken by the SAFER project team (Gilder et al., 2019a). Inconsistencies within the dataset were realized from early data optimization work, which sought to standardize the borehole logging descriptions. This assessed the quality of logging and geotechnical laboratory testing information recognizing that soil variability can be affected by: e.g., ‘equipment and procedural controls’, deterministic information guised as soil test data, ‘temporal changes in the soil’ due to testing dates and geological age (Phoon and Kulhawy, 1999a).

The soils in the Kathmandu Valley are characterised by interlaminated sequences, which presents problems for engineers especially where available drilling reports provide only partial recovery profiles. Fig. 1 describes such an instance where the database optimization procedure proved essential: the main constituent of the soil is interpreted, and changes are made to include correct descriptive terms of engineering strength. The soil profile shows where the material constituent in original logs are corrected based on evidence from laboratory testing. When the in situ standard penetration test (SPT) extended through multiple material types this presented difficulties for the derivation of soil strength parameters. These unconsolidated soils in the study area, of Pliocene to Pleistocene age (e.g. Sakai et al., 2008), often cause the SPT spoon to self-drive under its own weight. This is important non-numeric information to retain within the SPT dataset. Additionally, given the expected multi-constituent sampling, (as the soils are typically varved, lacustrine or deltaic) the volume of soils used in laboratory tests may not be considered truly representative. This might present instances where the original logging descriptions are most informative of grain-size. In these cases, information of the actual behaviour of the soils should be determined from the qualitative information provided in the original log and it is important that the database is checked prior to any subsequent analysis.

3 Methodology

The main aim of the research was to establish possible correlations to predict shear wave velocity (V_S), due to the severe lack of direct downhole measurements of the parameter in the region (Gilder et al., 2020). $G_{max} = \rho V_S{}^2$ describes the relationship between measured shear-wave velocities; where V_S *is* collected during geophysical tests, G_{max} is the in situ value of shear modulus at very small strains and ρ is the bulk density (e.g. Kramer, 1996).

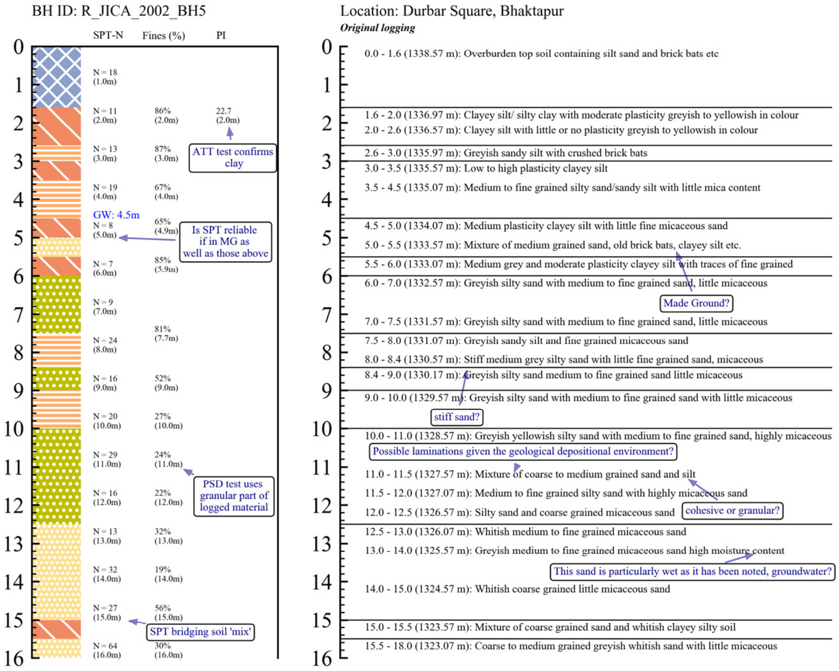

Fig. 1 Example of checked borehole dataset noting suggested changes and interpretations.

Prior to regression analysis using the dataset, a review of methodologies for the N versus V_S pairings was conducted. Most empirical correlations available are described using a power law in the form of Eq. (1) (e.g. Fabbrocino et al., 2015):

$$V_S = \mathrm{a}(N)^{\mathrm{b}} \tag{1}$$

where a and b are regression constants and N is uncorrected SPT blow count. Many equations are available for region specific cases (Wair et al., 2012). Commonly, case histories discuss the use of corrected or uncorrected SPT values and the soil-type categories used. However, the engineering judgements made to complete the pairing process are often not discussed in detail. Problems with pairing of individual N values with velocity measurements over a profile is generally acknowledged (e.g. Pitilakis et al., 1999). Similarly, N correction factors can be used to normalise the values to an overburden pressure of 100 kPa, (N_1) and corrected energy ratio of 60%, to the parameter $(N_1)_{60}$ (Skempton, 1986), yet studies in some cases have concluded correlations using normalised values can produce less accurate results (Wair et al., 2012). Fig. 2 compares a possible methodology for N and V_S pairings. The studied pairing methodologies can provide differing frequency of pairing results (i.e. number of data pairs). Three possible methods have been identified, Method 1, where incremental values of shear-wave velocity are paired with single values of N; Method 2, interval derived velocities with any corresponding single N values; and Method 3, interval derived velocities with *N* values averaged in each geophysical layer for soil type. These observations raised the following questions: (a) which methodology can be considered most reliable? (b) how do the possible errors in these methods carry forward into any developed correlations? and, (c) does correcting the *N* data improve the correlations in this case study?

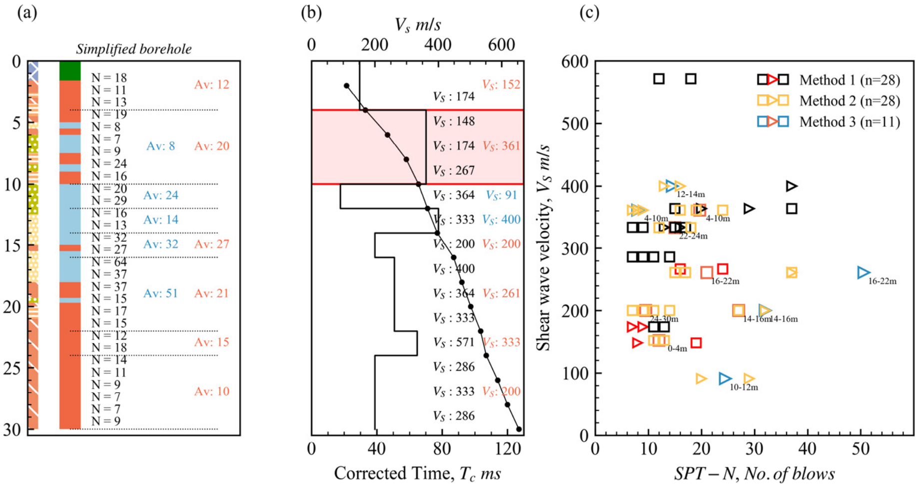

Fig. 2 Possible methods of interpretation to develop *N* and V_S pairings: (a) example of how a borehole record *N* values may be simplified; (b) possible interpretation of shear-wave velocity data with velocities calculated by increments (Method 1) or by velocity interval (grouping by similar slope, *m* of time data) (Method 2 and 3); (c) possible *N* and V_S pairs (n = number of data points).

4 Statistical analysis

4.1 N versus Vs pairing approaches

The previously discussed options for *N* and *Vs* pairings were investigated using regression analysis. Fig. 3 shows the results. On initial assessment, it was clear that in all the cases studied, the correlations have very low values of the coefficient of determination (R^2). The strongest correlation obtained used Method 1 (Fig. 3a), when using the equation in the form of Eq. (1). However, the transformation model of Method 1 involves introducing sub-intervals into the velocity data. This has produced higher calculated shear wave velocity data; reaching 900-1200 m/s within materials which are described as medium dense to very dense sand and 550-950 m/s in clayey silt. These higher values are the reason for the apparent stronger R^2 in Method 1. Four values were omitted due to being unrealistic (greater than 1500 m/s). Arguably Method 1 is inappropriate for this specific dataset, as when using a single receiver in downhole measurements calculation is best completed using the 'direct method' (see Kim et al. (2004)). With further comparison, Method 2 (Fig. 3b) shows velocities at a maximum of 620 m/s

(G_{max} of about 730 MPa) which are perhaps more realistic (at the upper end of the range shown in Oztoprak and Bolton (2013)). However, again, there are possible disadvantages: duplicates of the velocity data are produced depending on how many SPT-N values are available in each layer which introduces a bias of layer thickness. This effect is usually evaluated by producing histograms or box plots of variables held in a dataset and is an inherent part of the procedure. Lastly, the results of Method 3 (Fig. 3c) present averaged N values with V_S, thus removing the duplication effect, yet indicating the data is still poorly correlated.

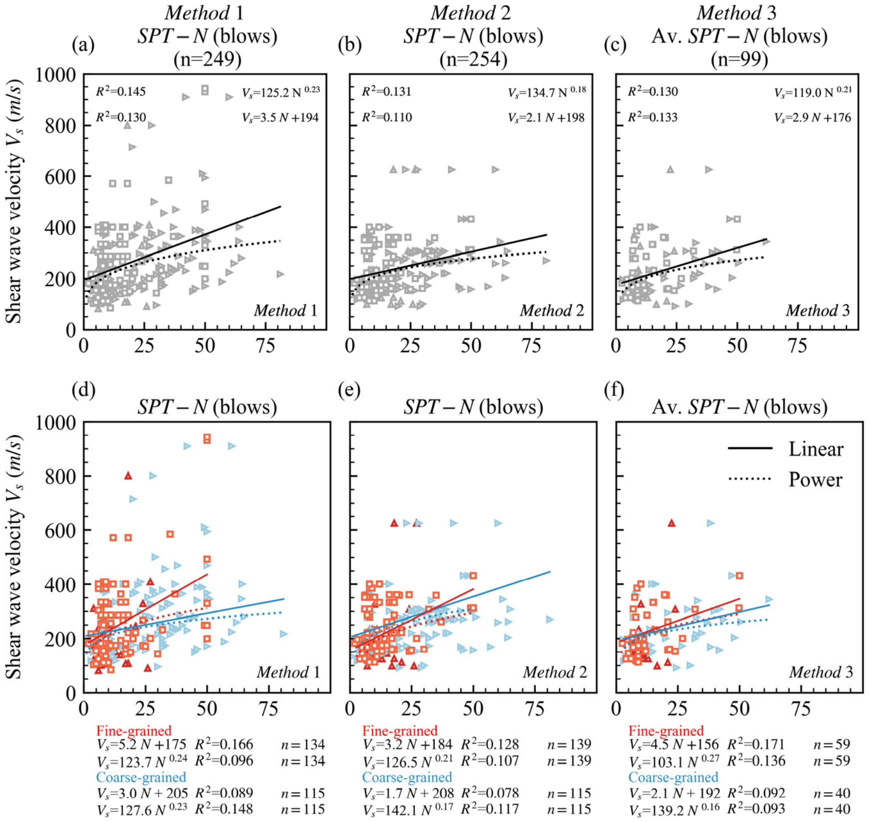

Fig. 3 Comparison of methodologies for N and Vs group pairings. (a) Method 1: incremental values of shear-wave velocity are paired with single values of SPT-N. (b) Method 2: time slope derived velocities with any corresponding single N values. (c) Method 3: time slope derived velocities with N values averaged in each geophysical layer for soil type. (d) Method 1, (e) 2 and (f) 3 separated for soil type; fine-grained: silt and clay, coarse-grained: sand and gravel.

Fig. 3a shows that the high synthetic values produced by essentially a misinterpretation of the velocity data do result in a slightly better correlation (i.e. higher R^2). However, the values of V_S obtained are often unrealistic given the soil types present. Although the R^2 values are lower (in this case) for Method 3, the transformation models probably are the best representation of reality. Fig. 3d to Fig. 3f show results separated for material type. When comparing the fine-grained and coarse-grained correlations the coarser soils show weaker correlation results (for Method 3). However, a similar result was noted by Fabbrocino et al. (2015) using this conventional approach. The heterogeneity of the Kathmandu soils as described in Section 2 affects the ability to produce meaningful correlations and the separation for material types did not significantly improve the results. Additionally, the use of the parameter $(N_1)_{60}$ was investigated and this also did not improve the correlations. Additional complications were found when plotting N with depth and the materials appear to have no evidence of consolidation in the upper 30-35m resulting in a general lack of increase in stiffness (Gilder et al., 2020). Finally, the data was analysed according to estimated geological age using elevation as a proxy. This is relevant as this region contains stacked sequences of lake and deltaic sediments, within a tectonic basin of metamorphic bedrock (Sakai et al., 2008). The results were marginally better for the elevation category (less than 1310 MASL) representing the more homogenous Kalimati Formation (lake deposit), but not for the upper categories of elevation.

4.2 Correlations with geotechnical parameters

Transformation models with a single predictor were determined for the basic geotechnical parameters studied (see Fig. 4): all the transformation models have low R^2 values. Multiple-linear-regression analysis produced the following relationship (Eq. 2) to predict V_S from a combination of N and water content (w):

$$\ln(V_S) = 0.24\ln(N) + 0.11\ln(w) + 4.29 \qquad (2)$$

Eq. (2) was found to have an $R^2 = 0.28$ for $n = 342$ (using pairing Method 2, noting that a single V_S-N pair may correspond to multiple values of w in the zone of interest hence increasing the n value for the regression). This analysis suggests that that reliable transformation models to predict shear wave velocity in the Kathmandu Valley cannot be developed using SAFER/GEO-591.

5 Summary and conclusions

In the case of the Kathmandu Valley, using a database of over 500 borehole logs (across an area of approximately 500 km^2), the developed transformation models linking various parameters to Vs exhibit significant data scatter about the regression lines. The methodology for pairing N and Vs measurements produces differing correlation results. The data obtained from the very soft to soft and loose soils in the Valley make for poor predictors when using these traditional methods as shear wave velocity data are concentrated in the lower portions of a possible dataset. Linear regression methods do not consider the geospatial effects and in the Kathmandu Valley this has proven to be significant. Until suitable relationships can be established using further high-quality in situ measurements, geospatial visualisation should be preferred in this region. It is recommended that the closest data points are used directly, if the geological conditions comply with the site of question, to make engineering decisions. Alternatively, summary statistics are provided for the database (Gilder et al., 2020) and shear wave velocity has been presented spatially using Bayesian kriging (De Risi et al., 2019) producing an improved presentation.

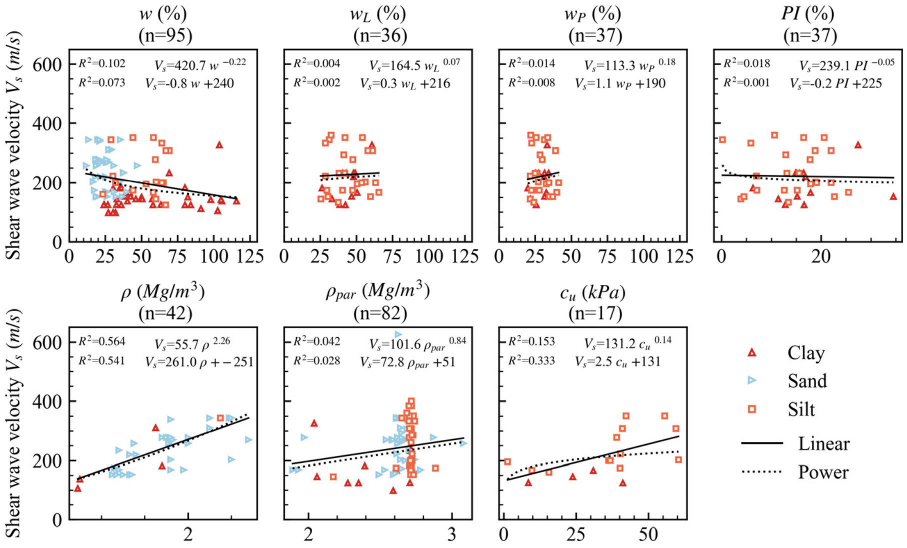

Fig. 4 Database geotechnical parameters against shear-wave velocity. Liner and power law transformation models shown. Plots provide duplicate values if more than one test is in each geophysical layer. (w = water content (%); w_L = liquid limit (%); w_P = plastic limit (%); PI = plasticity index (%); ρ = bulk density (Mg/m³); ρ_{par} = particle density (Mg/m³) and c_u = undrained shear strength (kPa)).

Acknowledgements: The first author acknowledges the support of the Engineering and Physical Sciences Research Council (EPSRC) (EP/R51245X/1). The authors also acknowledge the support of the EPSRC project (EP/P028926/1). *Data Availability:* the dataset used to produce the figures is available from Gilder et al. (2019b).

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