Further analysis of CPTu and seismic cone data collected in the Kathmandu valley, Nepal

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Abstract. The SAFER project had the aim of developing improved tools and enhanced datasets for seismic hazard assessment in Nepal. The project developed a geotechnical database for the Kathmandu valley (SAFER/GEO-591). During the project additional geotechnical site investigation data was collected including standard penetration testing and new borehole logging. Significantly, new Cone Penetration Testing (CPT) was carried out. This paper presents some further analysis of the collected CPT data and compares the test results against previously published analysis frameworks. The use of CPT data to estimate soil shear wave velocity in the Kathmandu valley along with normalisation procedures to account for the effects of stress level is discussed. Use of the new CPT data along with established soil classification charts is also presented in this paper.

Keywords: Cone Penetration Testing; Kathmandu valley; Gorkha Earthquake

1 INTRODUCTION

1.1 Background

The Gorkha earthquake (M_w 7.8) occurred in Nepal in 2015 (Goda *et al.* 2015). Substantial damage was experienced around the Kathmandu area (Chiaro *et al.* 2015, Goda *et al.* 2015, Ohsumi *et al.* 2016, Sharma and Deng 2019). The SAFER project aimed (in part) to develop new scientific knowledge to help improve the earthquake resilience of schools in Nepal. For geotechnical earthquake engineering, the average of shear wave velocity (V_s) from the ground surface to 30m depth (V_{s30}) is often used to classify soils in earthquake prone regions (e.g. CEN 2004). One major output of the project was the SAFER/GEO-591 database (Gilder *et al.* 2019a, 2020) which contains almost 600 borehole records along with associated soil index test data where available. SAFER/GEO-591 was developed using the Association of Geotechnical and Geoenvironmental Engineering Specialists (AGS) data format (AGS 2017) as a guide. During the building of SAFER/GEO-591, it was observed that few V_s measurements were available for the Kathmandu valley (see also Gilder *et al.* 2018).

1.2 Shear wave velocity measurement in the Kathmandu valley

High-quality V_s measurements are available at only a few sites in the Kathmandu valley (Gilder *et al.* 2018, 2021a). New V_s measurements were taken in two new boreholes carried out during the SAFER project (Gilder *et al.* 2019b, Pokhrel *et al.* 2019) using the downhole and the Horizontal to Vertical Spectral Ratio (HVSR) methods respectively. Gilder *et al.* (2021a, b) reported new CPTu testing from seven sites in the Kathmandu valley which increased the number of V_s measurements for this data-scarce region.

To mitigate the minimal numbers of direct measurements of V_s, the Standard Penetration Test blow count (SPT-N) is often used to estimate V_s or V_{s30} using local (or global) transformation models (see

Phoon and Kulhawy 1999a, 1999b for more details on the use of transformation models and transformation uncertainty in geotechnical engineering) (see Gilder *et al.* 2021c for some work on *Vs-SPT-N* transformation models for the Kathmandu valley). Such transformation models along with the available V_s data have been used to produce V_{s30} maps of the valley (cf. Gautam and Chamlagain 2016, Gilder *et al*. 2018). Recently updated V_{s30} maps for the Kathmandu valley have also been prepared using Bayesian Kriging (De Risi *et al.* 2021) and a multi-Gaussian Bayesian updating framework (Gilder *et al.* 2022). Accuracy of such Kriging methodologies can be improved with access to enhanced geotechnical databases and further CPT data (see Gilder *et al.* 2021a). Vardanega *et al.* (2023) have proposed a six-step methodology for development of geodatabases in data-scarce regions.

1.3 Paper outline

This paper presents some additional analysis of the CPT data presented in Gilder *et al.* (2021a) (see the thesis of Gilder (2022) for further details on the data collection and analysis). Use of the new CPT data allowed the SAFER project team to mitigate some of the data-scarcity issues encountered in the study area. In this paper the following topics are studied: soil classification (Section 2.1), normalisation of V_s (Section 2.2), pore pressure effects (Section 2.3) and further development of Kathmandu valley specific transformation models for V_s (Section 3).

2 CPT DATA FROM THE KATHMANDU VALLEY

2.1 Soil classification

The Kathmandu valley soils can be classified as 'unusual soils' according to the multiple definitions from Schnaid *et al.* (2004) as 'intermediate soils' and with general characteristics in the category of 'difficult soft soil conditions' (see Table 1 from Schnaid *et al.* 2004 for further details). Evaluation of in situ soil behaviour using CPT results is aided by Soil Behaviour Type (SBT) charts. Application of these methods can depend on many factors, including soil origin, deposition, ageing and cementation (cf. Schnaid *et al.* 2004). Application of typical transformation models and normalisation procedures may lead to uncertainty in the assessed hazard level and evaluation of liquefaction triggering potential as these models may not have been calibrated by soil test data similar to that of the study region (in this case the Kathmandu valley).

2.2 V_s normalisation

Often V_s is normalised when developing transformation models. The exponent on V_s (also discussed in the context of small strain shear modulus, $G_{max} = \rho V_s^2$) (ρ = soil density) (e.g. Fioravante *et al.* 1998) may vary. The overburden corrected normalised V_s parameter V_{s1} can be defined using Eq. 1 (e.g. Youd *et al.* 2001):

$$V_{s1} = V_s \left(\frac{P_a}{\sigma'_{v0}}\right)^{\nu} \tag{1}$$

where ν is the shear-wave velocity normalisation stress exponent often taken as 0.25 (see the discussion e.g. in Youd *et al.* 2001, Kayen *et al.* 2013, Moon and Ku 2016), P_a is atmospheric pressure, σ'_{vo} is the vertical effective stress (same units as P_a).

To predict V_s when in situ test data is not available, Robertson (2009) provides contours across the normalised cone resistance (Q_{tn}) – Normalised Friction Ratio (F_r) chart for V_{s1} verified using data from many regions (intended for uncemented Holocene and Pleistocene age sandy soils, see Robertson 2009). The V_{s1} results from all granular results (soil behaviour type index (I_{SBT}) > 2.6) for the Kathmandu study are plotted on Figure 1 and compared against the contours for V_{S1} from Robertson (2009), assuming ν = 0.25. The chart appears to over-estimate the calculated V_{s1} values for the granular sediments for the Kathmandu valley as many of the CPT data with values between 100 and 150 m/s fall within the chart region of 150-250 m/s.

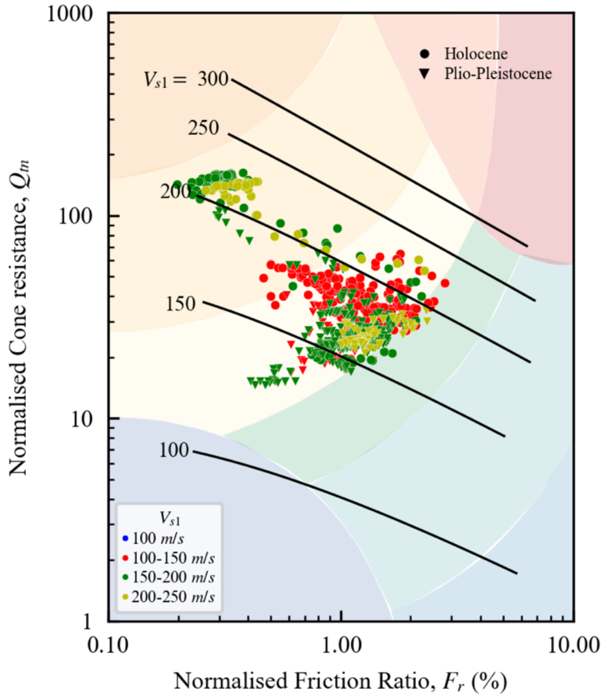

Figure 1. Robertson (2009) SBT chart with V_{S1} contours for estimation of V_s, plot shows the Kathmandu valley coarse-grained data separated by the calculated value of V_{S1} from the SCPT measurements (test data from Gilder *et al*. 2021a, b) (see also Gilder 2022).

2.3 Pore Pressure Effects

Figure 2 shows data from CPT site 06 and site 03 (see Gilder *et al*. 2021a, Gilder 2022 for a full description of all the test sites) plotted on the Schneider *et al.* (2008) classification chart. At site 06 (Figure 2a) in central Kathmandu, the lacustrine facies silts plot at the transition of Zones 1b and 1c, thus suggesting clay-like and sensitive clay behaviour. At site 03 (Figure 2b), the depositional environment is fluvio-deltaic and this data plots in zones describing sensitive clays, clays, silts and transitional soils.

Schneider *et al.* (2008) report that a larger $\Delta u_2/\sigma'_{vo}$ indicates an increase in Over Consolidation Ratio (OCR) or increase in undrained behaviour. Site 06 (and site 04) are at low-lying points in the basin, underlain by the older Kalimati Formation soils, so probably have a slightly greater stress history than the marginally younger fluvio-deltaic deposits. However, oedometer test results in the SAFER-GEO/591 database (Gilder *et al.* 2019a, 2020) indicated under-consolidated soils (see e.g. Denissov 1965 for a discussion on under-consolidated soils). Close to site 06, OCR is estimated to be in the range 0.8-1.0, while within similar deposits to those encountered at site 03, OCR is approximately 0.90 (stated values relate to 9 m depths). Differences in plasticity in the Kathmandu soils also seem to affect where the soils plot on the Schneider *et al.* (2008) chart i.e. the lower plasticity silts lie close to the drained, sand-like portion of the classification charts, whereas higher plasticity soils follow the anticipated increase in OCR.

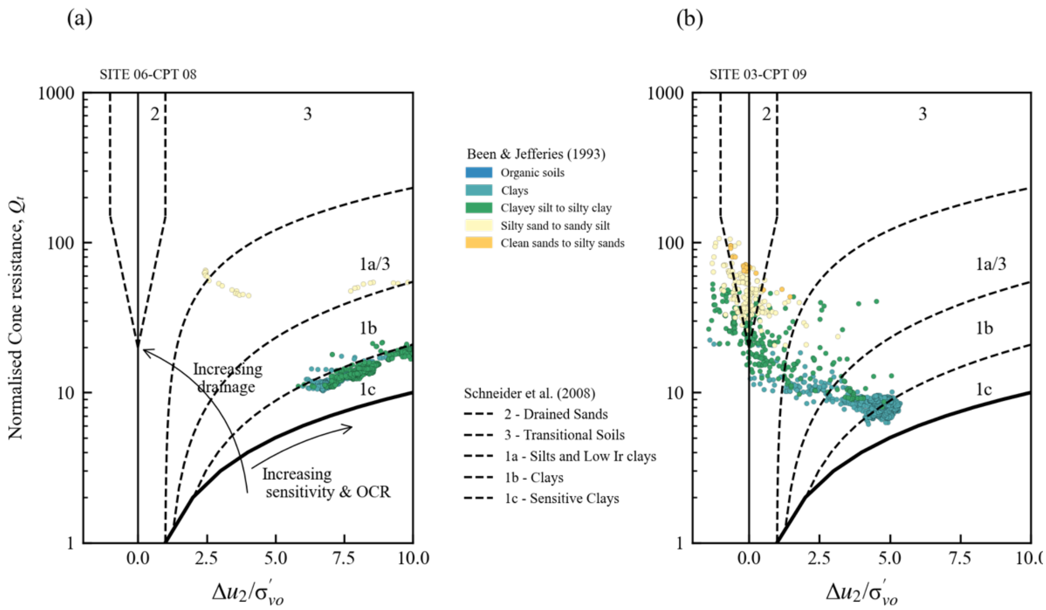

Figure 2. Schneider *et al.* (2008) plot with data points classified using Been and Jefferies (1993) definition of soil behaviour type (a) site 06, Chyasal (b) site 03, Kausaltar (test data from Gilder *et al.* 2021a, b) (see also Gilder 2022).

3 TRANSFORMATION MODELS

3.1 Correlation of shear wave velocity with vertical effective stress

The Robertson (2009) contours for V_{S1} on the Q_{tn}-F_r chart use v equal to 0.25 for sands (as often used for liquefaction assessments) (cf. Youd *et al.* 2001 and Kayen *et al.* 2013). In the studies of Ku *et al.* (2017) and Moon and Ku (2018) transformation models of the form shown in Eq. 2 were fitted to data of V_s (m/s) and σ'_{v0} (kPa):

$$V_s = \alpha(\sigma'_{v0})^{\beta} \tag{2}$$

where α and β are curve fitting parameters.

Moon and Ku (2018) analysed a large geotechnical database and found the following relationship linking V_s (m/s) and σ'_{v0} (kPa) (Eq. 3) for cohesive soils:

$$V_s = 12.64(\sigma'_{v0})^{0.53} \quad [n = 345, R^2 = 0.64] \tag{3}$$

where n is the number of data points used to generate the regression and R^2 is the coefficient of determination.

A similar relationship was found for clay soils by Ku *et al.* (2017) given as Eq. 4 (V_s in m/s and σ'_{v0} in kPa):

$$V_s = 12.47(\sigma'_{v0})^{0.54} \quad [n = 374, R^2 = 0.92] \tag{4}$$

Ku *et al*. (2017) for a larger database (n = 802) of various soil types (e.g. sands, silts and clays) computed values of α = 26.56 and β = 0.42.

Figure 3 shows that the Moon and Ku (2018) transformation model compares with the CPT data from Nepal reasonably well in the central portion of the data-set (approximately $40 < \sigma'_{v0} < 110$ kPa). However, when the low and high σ'_{v0} values are included, the regression for the new CPT data (V_s in m/s and σ'_{v0} in kPa) gives a lower value of the β parameter:

$$V_s = 67.0(\sigma'_{v0})^{0.17} \qquad [n = 49, R^2 = 0.25] \qquad (5).$$

To check the validity of the values of the exponent for the Nepal CPT data a comparison against the database of Ku *et al.* (2017) is given in the box plot shown as Figure 4. The computed exponents for the new CPT data are just outside the ranges from the database presented in Ku *et al.* (2017).

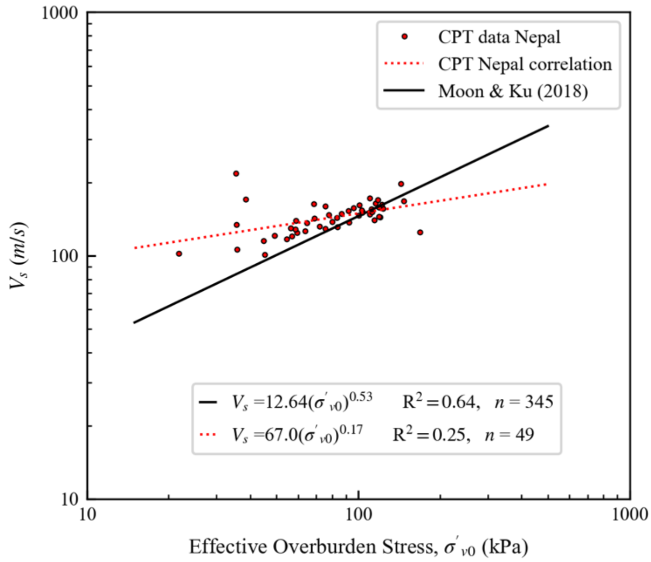

Figure 3. Transformation models linking V_s with effective stress (test data from Gilder *et al*. 2021a, b) compared with Eq. 3 (originally proposed by Moon and Ku 2018) (see also Gilder 2022).

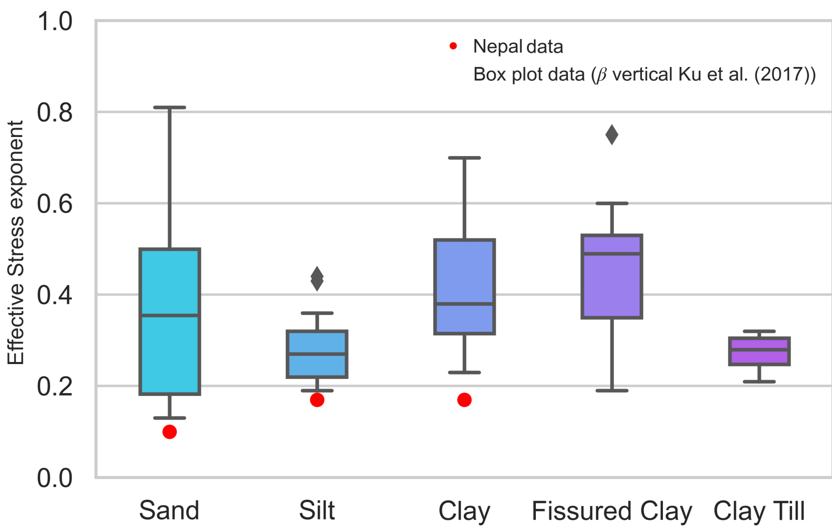

Figure 4. Box-plot comparison of Ku *et al.* (2017) database with effective stress exponents computed from the Nepal CPT data by soil type (data from Gilder *et al.* 2021a, b and Ku *et al.* 2017: see the paper online supplement) (see also Gilder 2022).

3.2 Correlation of shear wave velocity with cone tip resistance

Figure 5 shows the range of corrected total cone tip resistance (q_t) values available from this study. Figure 5a illustrates that no clear correlation is evident for this dataset. Figure 5b shows locations likely underlain by River Terrace deposits, which in the upper 5 m, have higher q_t values. High q_t values also correspond to coarser-grained layers at depth. The Pliocene to Pleistocene data is mostly of silts and clays of a similar composition and the results are localised within the approximate ranges of 0.25-3 MPa for q_t and 100-200 m/s for the V_s measurements respectively.

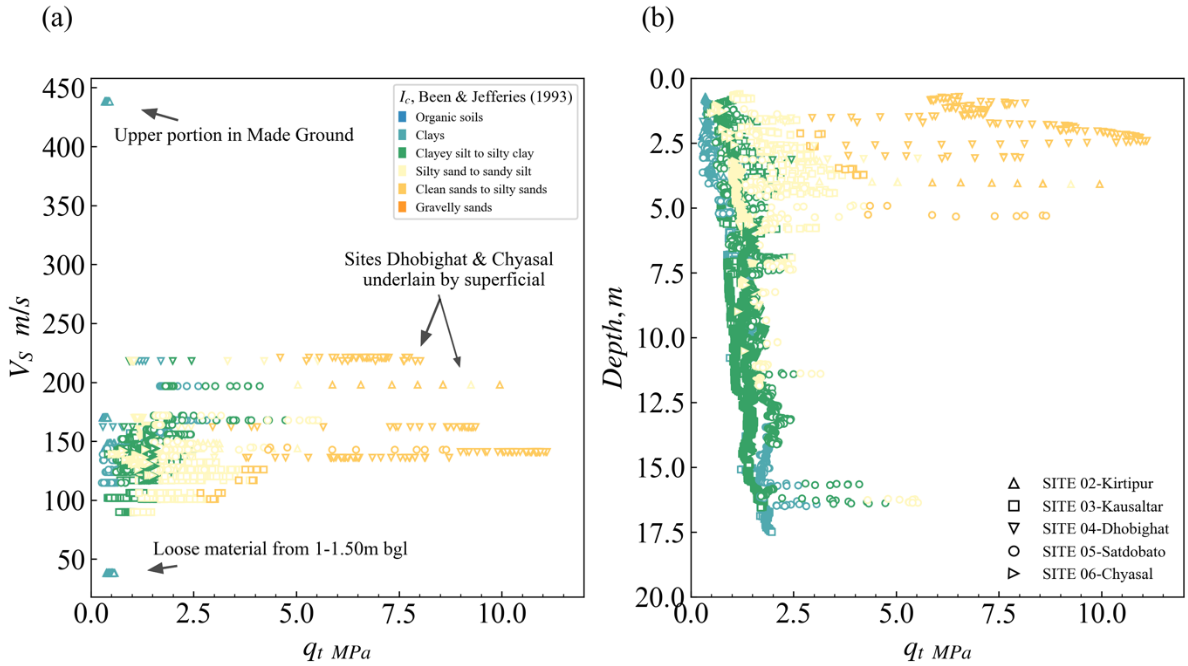

Figure 5. (a) Range of q_t values over each increment of V_s measurement (b) variation of q_t with depth (test data from Gilder *et al.* 2021a, b) (see also Gilder 2022).

4 CONCLUSIONS

This paper has presented further analysis of the CPT data presented in Gilder *et al.* (2021a). The limited CPT data currently available for the Kathmandu valley soils tends to be in the 'intermediate zone' in CPT soil type classification. The use of the Schneider *et al.* (2008) chart has allowed the soil types and drainage state to be better distinguished in this zone, which may help determine areas of liquefiable and non-liquefiable soils in the Kathmandu valley. Using the Robertson (2009) contours for V_s prediction from CPT parameters generally results in an over-estimation of V_s for the soils in the study area. Previously established transformation models from Ku *et al.* (2017) and Moon and Ku (2018) for clay soils do match the new CPT dataset reasonably well in the range 40kPa < σ'_{v0} < 110kPa but when data outside this approximate range are included the effective stress exponent reduces to a low value < 0.2. A clear correlation between V_s and q_t was not found for the studied soils.

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DATA AVAILABILITY

The CPT data is available from the University of Bristol Research Data Repository (Gilder *et al.* 2021b). The SAFER/GEO-591 database can be downloaded from the University of Bristol Research Data Repository (Gilder *et al.* 2019a).

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