GEOTECHNICAL VARIABILITY OF THE SOILS IN THE KATHMANDU VALLEY, NEPAL

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Abstract

The 2015 Gorkha earthquake caused considerable infrastructure damage and disruption. In the years that followed, the need emerged for planners to access hazard maps and better plan future developments and upgrades to existing infrastructure assets. In light of this, the ability to run stochastic simulations is important for scenario planning. When modelling geotechnical phenomena soil variability needs to be assessed. For stochastic modelling efforts, soil variability should be assessed statistically. There are two key geological units in the Kathmandu valley: the Gokarna and Kalimati formations. These valley sediments are highly variable but high-quality geotechnical data is scarce. To mitigate this data scarcity, a recently developed geotechnical database called SAFER/GEO-591 is used to determine the best fit probability density functions for key soil parameters in each formation relevant for geotechnical design and modelling efforts. The best-fit probability density functions can be used in modelling liquefaction potential, site, and foundation response for new and existing constructions in the valley.

Keywords: Geodatabases, Soil Variability, Probability Density Functions, Kathmandu Valley

1. Introduction

In 2015 the Gorkha earthquake (7.8 Mw) struck the Kathmandu valley causing considerable structural damage to many buildings in the city [1-3]. The Engineering and Physical Sciences Research Council (EPSRC) project "Seismic Safety and Resilience of Schools in Nepal" (SAFER) has the aim of improving the seismic resilience of school buildings in Nepal. The SAFER project has also presented preliminary insights for new probabilistic seismic hazard analysis studies for the valley [4-5]. In addition to this work, a major output from the project has been the development of a new geodatabase for geotechnical properties of the soils of the Kathmandu valley [6-8]. This database has been used to investigate Bayesian kriging approaches to prepare and improve maps of soil shear wave velocity [9]. In this paper this database is used to evaluate the variability of the soils of the valley with the aim of assisting designers and modellers in the assignment of key geotechnical parameters for the main geological formations in the Kathmandu valley.

2. Geological and geotechnical characteristics of the Kathmandu valley

The Kathmandu valley has a complex geology (e.g. [10-14]). The SAFER project has undertaken new site investigation work in the valley, including new boreholes [15], HVSR testing [16] and cone penetration testing [16]. The Kathmandu valley has two key geologies: the Kalimati and the Gokarna formations (see Fig. 1 [14]).

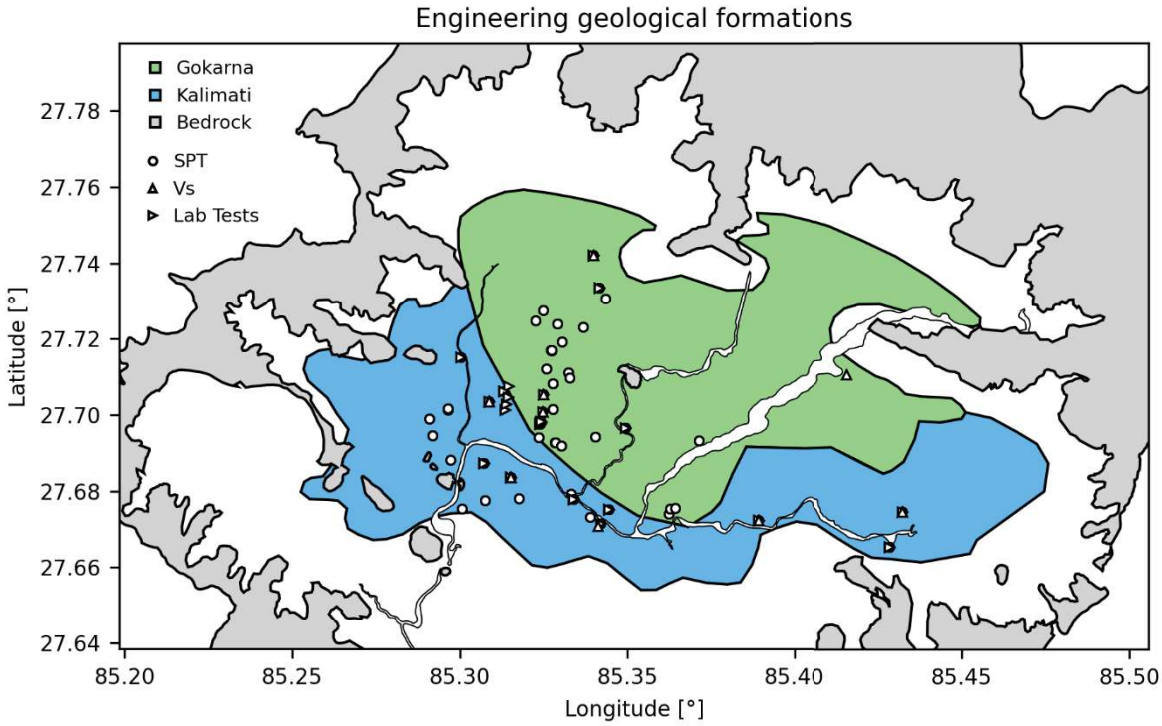

Fig. 1 – Map showing the two main engineering geological materials; Gokarna and Kalimati formations (for the more detailed engineering and environmental geological map of the Kathmandu valley see [14]). Location of the testing available in each formation is shown.

For a detailed review of the geological characteristics of the Gokarna and Kalimati formations see [8]. The two formations have different geological characteristics. Fig 2a shows a soil sample for the Gokarna formation taken during one of the SAFER geotechnical site investigations (for further details see [7,15]). Fig 2b shows a soil sample for the Kalimati formation taken during one of the SAFER geotechnical site investigations (for further details see [7,15]).

(a) (b)

Fig. 2 – Examples of (a) Gokarna formation (Photo credit C.E.L. Gilder) [7] (b) Kalimati formation (Photo credit R.M. Pokhrel) [7].

3. SAFER/GEO-591

Geotechnical engineers require databases to assign ranges of soil parameters during design and develop transformation models for prediction of key geotechnical design parameters [cf. 18-20]. Early papers by Lumb [21, 22] show the use of statistical methods to study the variability of Hong Kong soils. For the Kathmandu valley, Piya [23] and Piya et al. [24] presented an early geotechnical database for the Kathmandu valley. Gilder et al. [6,8] collected a large database comprising over 500 boreholes with associated geotechnical laboratory testing for the valley called 'SAFER/GEO-591'. The database has been released open access and is available from [6].

Gilder et al. [25] used SAFER/GEO-591 to investigate transformation models for prediction of more complex soil parameters from simpler ones. Gilder et al. [25] found the following relationship for shear wave velocity (Vs) with Standard Penetration Test blowcount (N) value and natural water content (w), Eq. 1.

$$\ln(Vs) = 0.24 \ln(N) + 0.11 \ln(w) + 4.29 \qquad [R^2 = 0.28,\ n = 342] \qquad (1)$$

Given the low coefficient of determination (R^2) of the transformation model it was decided to investigate the variability of key soil parameters by fitting probability density functions (pdfs) that best describe relevant soil properties.

Recent work for the soils of Saint Lucia [26, 27] has shown that the Weibull distribution is useful for describing variability of the soil friction angle. The results of a similar analysis, using the SAFER/GEO-591 database, is presented in the next section for the Gokarna and Kalimati formations.

4. Analysis

Data from the Gokarna and Kalimati formations have been extracted for different geotechnical parameters aimed at describing and comparing their variability. In particular, Standard Penetration Test blowcounts (SPT_N), shear wave velocity (Vs m/s), plasticity index (PI %), water content (w %), effective cohesion (c' kPa) and effective friction angle (ϕ' °) have been sourced from the database for the two formations. SPT_N represents the richest data category among the six parameters selected. For both Gokarna and Kalimati a comparable number of data points are available in the database (i.e., 1101 and 1169 SPT_N values for Gokarna and Kalimati, respectively). Another parameter typically used for soil classification, especially in earthquake-prone environments, is Vs, for which 25 and 39 data points are available, respectively. Fig 3 shows the empirical pdfs

of SPT_N and V_s in the two formations. A preliminary inspection of the data does not reveal significant differences between the ranges of these parameters and the only notable aspect is the difference in shape of the empirical pdfs for SPT_N for the two formations (Fig. 3).

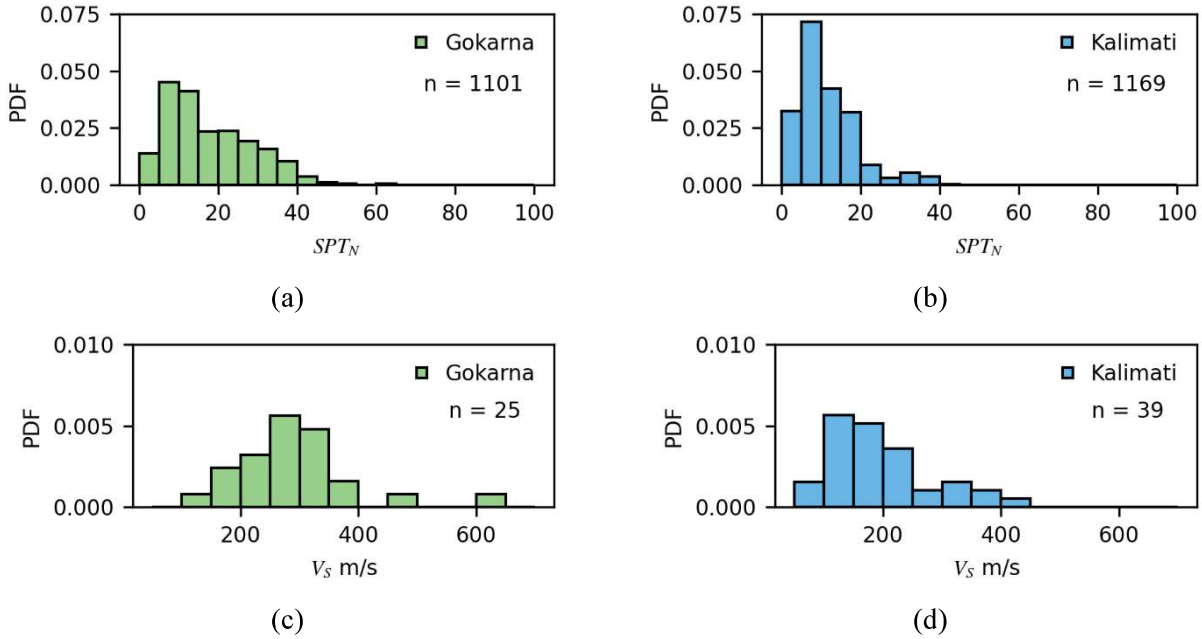

Fig. 3 – Probability density functions of SPT_N and Vs in (a) and (c) the Gokarna and (b) and (d) the Kalimati formation, respectively.

For the case of *PI*, the database contains 44 estimates for the Gokarna and 112 for the Kalimati formation. A comparison of the empirical pdfs shows different ranges, and the shape of the distributions of the Gokarna formation seems more concentrated in a smaller value range, see Fig 4. These distributions reflect what is expected when considering the origins and likely grainsize distributions of these materials, see [6]. The Gokarna Formation contains for the majority sands and silty sands, which show lower natural water contents and for those containing a cohesive content some plasticity, see Fig 4a and Fig 4c respectively. Fig 4a shows a peak where much of the data is 'Non-Plastic'. The Gokarna Formation also contains lenses of fine-grained and organic materials as seen in Fig 2a which are represented by the solitary peak in Fig 4a at higher values of *PI* and the higher *w* values in Fig 4c. The Kalimati Formation is a lacustrine deposit which has a wider range of natural water contents, when compared to the Gokarna results, and a plasticity that centralizes at a *PI* of between 16-18%. The Kalimati is also reported to contain very few sand layers which are evident in the *PI* results in Fig 4b.

Strength parameters such as c' and ϕ' are available for a limited number of data points for the Gokarna formation (i.e., 19), while in the case of Kalimati formation a higher number is available (i.e., 49). The empirical pdfs of c' and ϕ' are shown in Fig. 5. The comparison of these distributions indicates that the Kalimati fine-grained materials exhibit a greater spread of values than the fine-grained materials in the Gokarna. The effective friction angle distribution of the Gokarna formation has a mode value of 30 degrees, which is higher than the mode of the Kalimati formation.

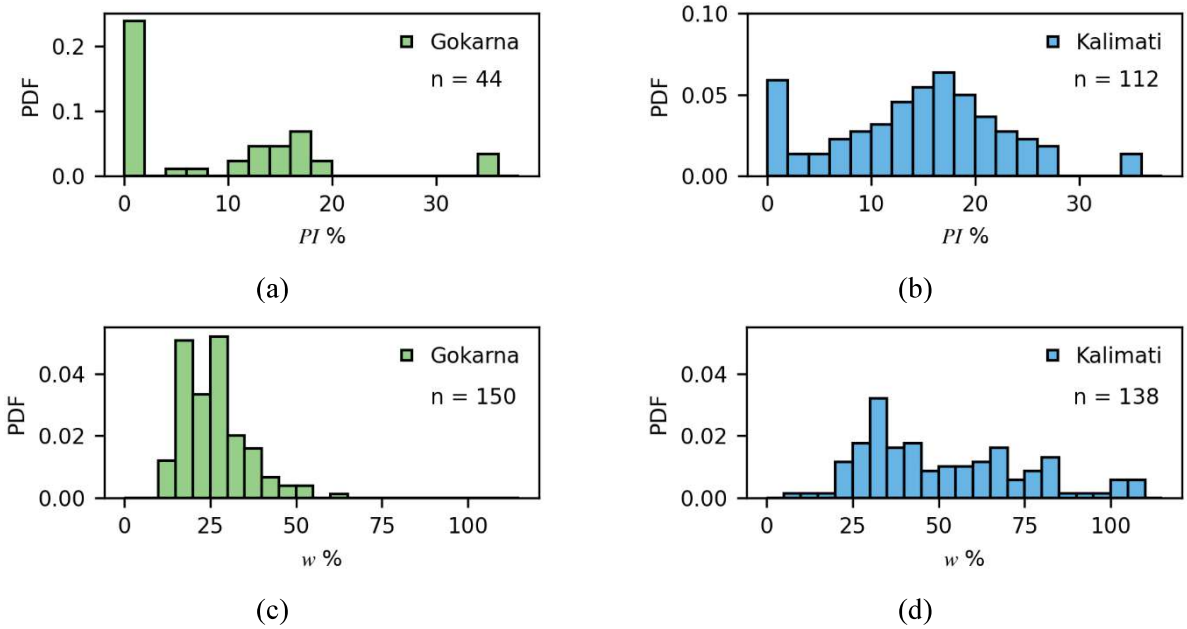

Fig. 4 – Probability density functions of *PI %* and *w %* in (a) and (c) the Gokarna and (b) and (d) the Kalimati formation, respectively.

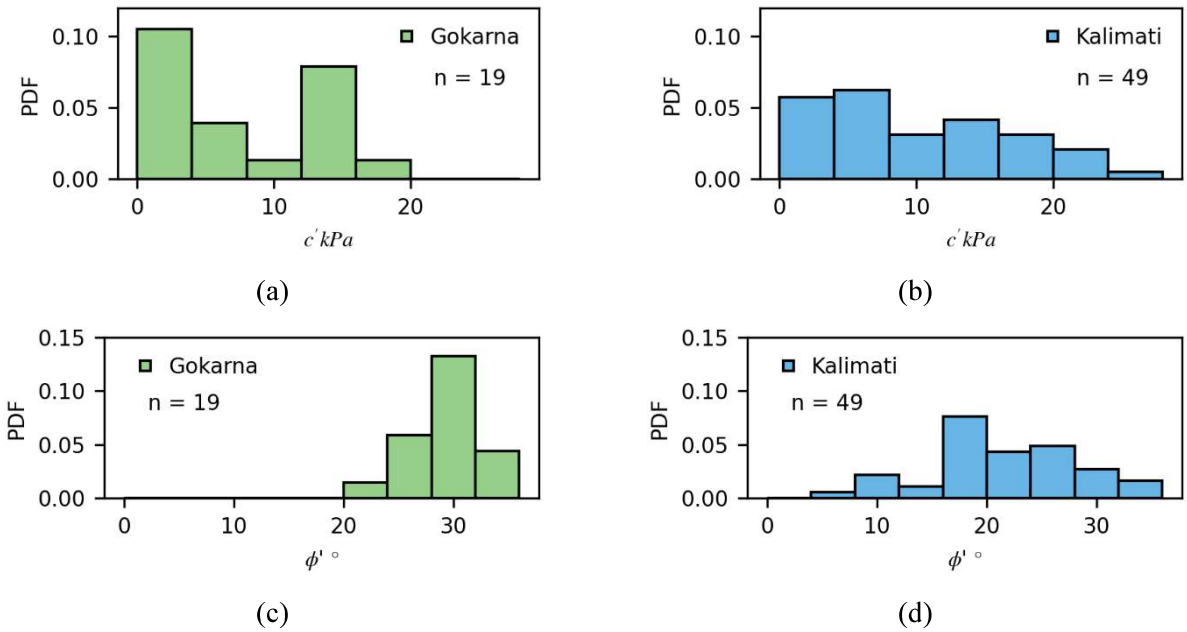

Fig. 5 – Probability density function of c' and ϕ' in (a) and (c) the Gokarna and (b) and (d) the Kalimati formation, respectively.

Data presented in the form of empirical pdfs in Fig. 3, Fig. 4 and Fig. 5 are fitted using conventional parametric distributions. Normal, Lognormal and Weibull parametric models are considered for the following parameters: SPT_N, Vs, w, c' and ϕ'. Typically, Normal and Lognormal models are widely used two-parameter models. In this case, the Weibull model is also considered as it was found to be the best fitting parametric distribution for friction angle of Saint Lucian soils [26]. Table 1 provides the values of the log-likelihoods for the five parameters considered for the two formations. Lognormal and Weibull distributions are those which provide the best fit of the data presented in Figs. 3 to 5 (see bold values in Table 1). The best fit evaluation is made on assuming the highest likelihood value.

Table 1 – Log-likelihoods values of fitted Normal, Lognormal and Weibull distributions. Bold indicates the highest log-likelihood for each geotechnical parameter.

Parameter	Log-likelihoods					
Geological Formation	Gokarna			Kalimati		
Distribution	Normal	Lognormal	Weibull	Normal	Lognormal	Weibull
SPT_N	-4265.48	-4146.9	**-4101.51**	-4060.96	**-3755.55**	-3824.36
V_S	-150.929	**-148.384**	-150.87	-226.315	**-221.441**	-224.61
w	-546.319	**-530.811**	-544.738	-634.699	-628.496	**-627.618**
c'	-63.2421	-45.9468	**-44.0298**	-166.883	-180.621	**-161.619**
ϕ'	-54.7102	**-54.5745**	-55.5845	-168.513	-170.916	**-168.265**

For the Kalimati formation, the Weibull model provides the best fit for c' and ϕ' as selected on the basis of the maximum likelihood. For the Gokarna formation, c' is better represented by a Weibull model and ϕ' by a Lognormal model. For this formation, only 19 data points are available so the best-fit model selection cannot be considered as reliable as in the case of the Kalimati formation where more than double the number of data points are available (i.e., 49). Since only two-parameter distributions were considered, the selection of best-fit model based on log-likelihoods can be considered reliable as there is no need to account for the number of parameters of the model. This can be done using other kinds of approaches to select the best fit model such as the Akaike Information Criteria [28] which weights in a single scalar index the number of parameters of the distribution, employed in [26] as one of the selection criteria together with the Anderson and Darling test [29]. The best fitting distribution models as selected in Table 1 are shown graphically in Fig.6 for SPT_N, c' and ϕ' and a Kolmogorov-Smirnov (K-S) goodness of fit test [30] is also performed to verify the model assumption. Fig. 6 provides the graphical representation of the K-S tests performed at 10% significance level. The K-S boundaries depend on the number of data available. SPT_N is best fitted by a Weibull model (Fig 6a) and Lognormal model (Fig 6b) for the Gokarna and Kalimati formations respectively. For the case of c' and ϕ' in the Gokarna formation (Fig. 6c and 6e), the best fitting models are Weibull and Lognormal, respectively. For the case of c' and ϕ' in the Kalimati formation (see Fig. 6d and 6f) the Weibull model is slightly better than the Normal distribution because of the way the tail data are fitted.

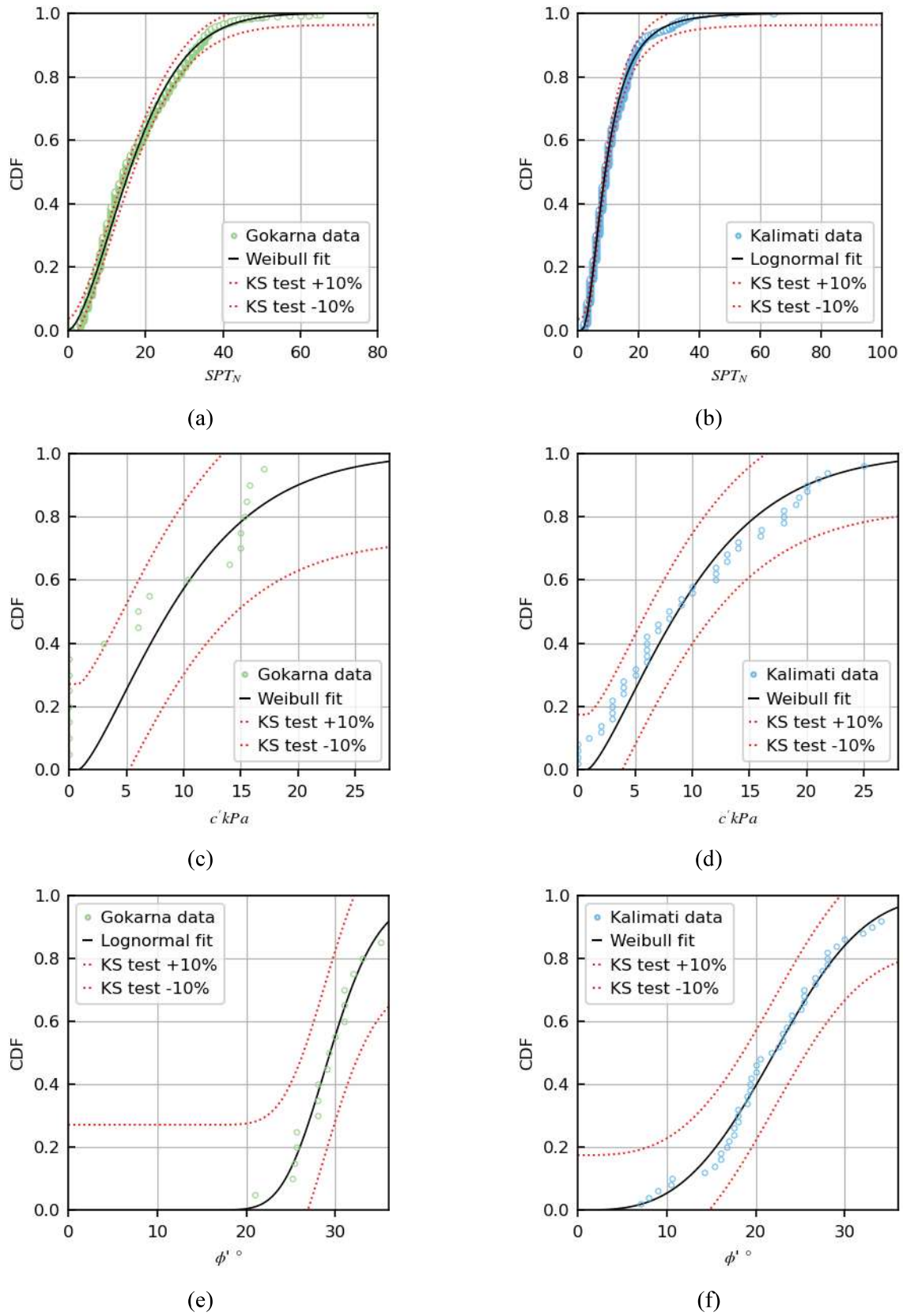

Fig. 6 – Cumulative distribution functions of SPT_N, c' and ϕ' data in the SAFER geodatabase for (a), (c), (e), the Gokarna and (b), (d), (f) the Kalimati formation, respectively and 10% K-S test boundaries.

5. Summary & Conclusions

This study provides information about the statistical variability of two of the main soil formations in the Kathmandu valley: the Gokarna and Kalimati. Data sourced from the SAFER Geodatabase of standard penetration testing results, shear wave velocity, plasticity index, water content, effective cohesion and effective friction angle have been used to determine the empirical probability density functions of the two formations and their value ranges. As new data becomes available, the Gokarna data should be split in order to examine the constituent fine and coarse-grained materials and improve the estimation of the fitted distributions.

Three model distributions have been used to fit the data and select the parametric model that provided the best fitting results. In the case of Kalimati, for which more strength data are available in the database, the Weibull distribution was found to be the best option for effective cohesion and effective friction angle as compared with other distributions in terms of log-likelihoods. The best fit was also verified using a Kolmogorov-Smirnov test. For the Gokarna formation, the Weibull was the best model for the effective cohesion but the Lognormal performed better for the effective friction angle.

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7. Data Availability

The data used to produce the figures and tables in this paper can be downloaded from [6].

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