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Spatial Variability of London Clay Using CPT and SPT Data

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Abstract: London Clay has been the subject of intensive investigations, but further research is required to characterize the spatial variability in greater detail. This study focuses on establishing a measure of the spatial variability using the Scale of Fluctuation (SoF), a key input into random field modelling of geotechnical problems. At two sites in Central London, the SoF is calculated using cone penetration tests (CPT) and standard penetration tests (SPT), both driven perpendicular to the lithostratigraphic sequence. The vertical interval (spacing) of CPT data is 0.02 m. The spacing of SPT data is ≥ 1.5 m. The results show that the vertical SoF from CPT is 0.24 – 1.01 m with a mean of 0.48 m; the vertical SoF from SPT is 0.96 – 3.99 m with a mean of 2.26 m. The SoF from SPT is close to the SPT data spacing, therefore the accuracy of SoF from SPT is questionable. The results also suggest that the main drivers for spatial variability are likely attributed to sedimentary cycles acting over thousands of years. The results do not provide sufficient resolution to evidence any seasonal variations.

Keywords: London Clay; spatial variability; scale of fluctuation; ground investigation, cone penetration test (CPT)

1 Introduction

Spatial variability forms a dominant source of uncertainty in geotechnical applications. Spatial variability can be characterised by the Scale of Fluctuation (SoF), which is a measure of the distance over which characteristic parameters of a soil or rock are similar or correlated (e.g. Cami et al., 2020). Reports on the SoF for stiff (overconsolidated) clays are sparse; a recent review by Cami et al. (2020) reveals only two publications, both targeting the Keswick Clay in Adelaide, Australia (Jaksa, 1995 and Jaksa et al., 1999). In the UK, many long linear geotechnical assets are cut into or composed of stiff clays of intermediate to high plasticity such as the London Clay and their gradual deterioration affects asset performance and lifespan (Briggs et al., 2017; Postill et al., 2020, 2021a, 2021b; Stirling et al., 2020; Svalova et a., 2021). The deterioration modelling of these assets requires detailed understanding of fluctuations in key parameters. Variations of London Clay properties for the various litho-stratigraphical units are widely reported for index properties (e.g., liquid limit, plasticity index, water content; Hight et al., 2003; Standing and Burland, 2006; Pantelidou and Simpson, 2007; Standing, 2020), and mechanical properties (e.g., undrained shear strength; Stroud, 1974; Cripps and Taylor, 1986; Hight et al., 2003; Standing and Burland, 2006; Pantelidou and Simpson, 2007). Major geotechnical works in the London Clay, such as those carried out for Crossrail (Sismondi and Weinmar, 2015) deliver further insights into spatial variations of London Clay. However, no study has been found that addresses the SoF of London Clay (Cami et al., 2020).

The SoF is a key input parameter for random field finite element analysis of geotechnical structures. Charlton and Rouainia (2019) investigated the cyclic behaviour of a laterally loaded monopile in spatially variable London Clay. Due to the lack of information on the SoF of London Clay, Charlton and Rouainia (2009) assumed the vertical and horizontal SoF to be 1 m and 10 m, respectively, based on typical properties of other soils. However, as London Clay is a stiff, high plasticity clay, therefore its SoF may deviate from that of normally consolidated and/or low plasticity clays.

This paper aims to study the SoF of London Clay which, in turn, will enable more realistic deterioration modelling of geotechnical assets in this material. A brief review of the geological setting of London Clay is first provided. This is followed by an investigation of the SoF of London Clay with cone penetration tests (CPT) and standard penetration tests (SPT) from two sites spaced 500m apart in central London. The SoF is then discussed in terms of the source of data and in the context of geological history of London Clay.

2 Geology of London Clay

London Clay is a marine deposit, that daylights across the London and Hampshire Basins of south-east England (e.g., Royse et al., 2012). For decades London Clay has been thought as a uniform and homogeneous material (Standing, 2020). King (1981) divided the London Clay Formation into five divisions from A to E, as shown in Figure 1. Each division recorded an initial marine transgression followed by gradual shallowing of the sea. The general principle of a coarsening upward sequence in each sedimentary cycle and subdivision is evident, the result of gradual shallowing of the water. It should be noted that the sequence stratigraphic divisions deviate from the lithological units (Ellison et al. 2004). The lithological units that formmally named and defined by King (2016) are also shown in Figure 1. However, the sequence stratigraphy division is more widely used, particularly in the field of geotechnical engineering (e.g., Hight et al., 2003; Pantelidou and Simpson, 2007; Standing, 2020). Hence, the sequence stratigraphy division is also used in this study and the main focus is on subdivision B2.

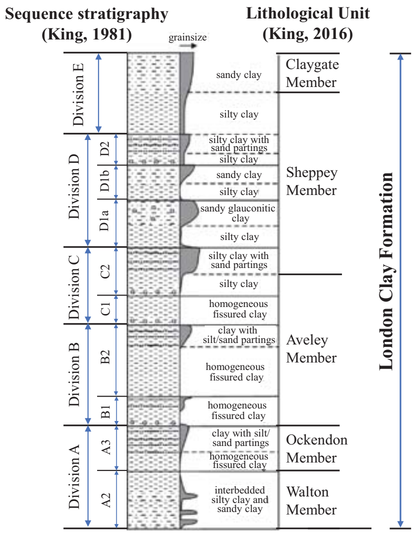
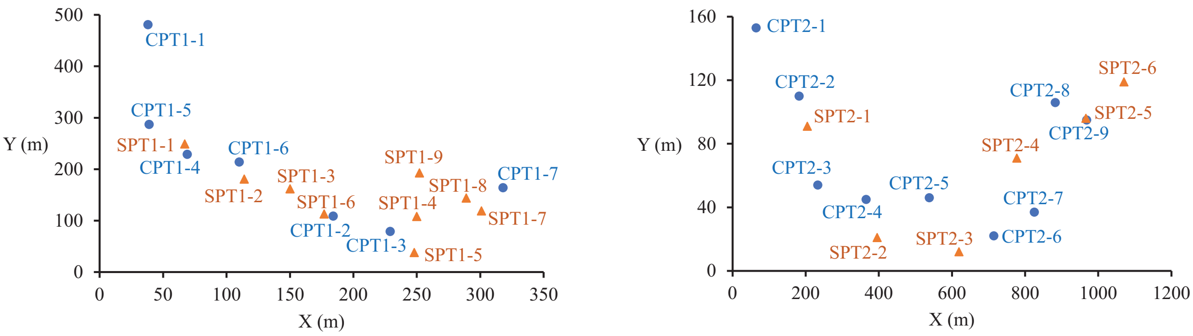


Figure 1. Stratigraphy of the London Clay Formation in the London area (after King, 1981, 2016; Royse et al. 2012)

3 Site information and data

The layouts of CPTs and SPTs are shown in Figure 2. Both sites are in Central London and within close proximity to Hyde Park. The closest distance of these two sites is about 500m. The SPTs were carried out as part of the borehole investigations. The borehole logs could be derived from the BGS National Geotechnical Database (Self et al. 2012), and they were used to characterise the ground. The main soil type is London Clay. However, London Clay can be further divided into divisions, as shown in Figure 1. A convenient way to differentiate the interfaces of the subdivisions is through the profile of natural moisture content (NMC) (Hight et al. 2003; Standing, 2020). As shown in Figure 3, the NMC is plotted with depth for both sites. The average NMC is used for the instance where there are multiple measurements at the same depth. Note that the reduced levels for elevation are expressed as "m AD", abbreviation for "meter above datum". The datum is set to be 100 m below Ordnance Datum Newlyn.



(a) Site 1 (b) Site 2

Figure 2. Locations of CPTs (in circle) and SPTs (in triangle)

The thickness of Tertiary strata removed by erosion in Central London is about 200 m (Pantelidou and Simpson, 2007), hence divisions C, D, and E shown in Figure 1 are absent in central London, and only divisions A and B are shown in Figure 3. The level of London Clay sub-divisions in the Hyde Park area suggested by Standing (2020) is 87.2m AD for the base of B1, and 88.7m AD for the base of B2. They are found to be valid for this study. The trend of an upward decrease of water content in A3 indicates an upward increase of coarse-grained content. The first few meters of B2 show higher moisture content, which may be attributed to the higher weathering grade. The boundary between units A and B is marked by a thin layer sandy clay (Unit B1) which is glauconitic (Hight et al. 2003).

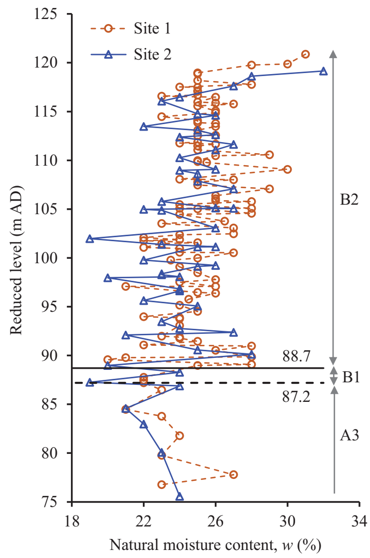
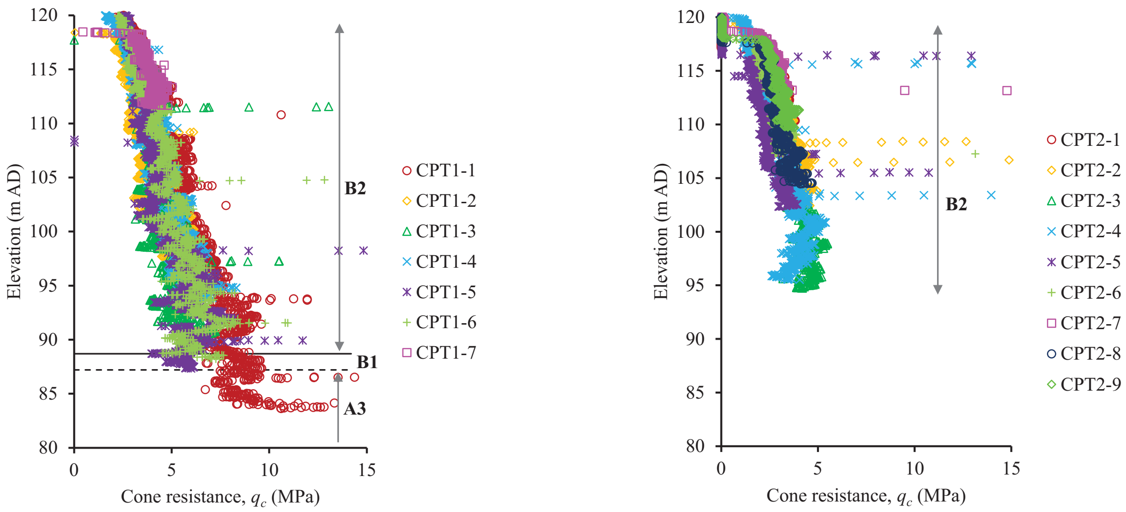


Figure 3. w-profiles and sub-divisions for Site 1 and Site 2

The CPT and SPT data used for spatial variability analysis are plotted in Figure 4 and Figure 5, respectively. The cone resistance, q_c, is the CPT parameter used in this study, as it can be correlated with many other soil properties and most often used for spatial variability analysis (e.g., Cami et al. 2020; De Gast et al. 2021). Both cone resistance and SPT-N increase almost linearly with depth. The linear trend has been removed for each set of data, and spatial variability analysis conducted on the residuals. Analysis has only been conducted for London Clay B2 subdivision, as only limited data is available for subdivisions B1 and A3. For the analysis of CPT data in Figure 4, the outliers, defined as more than three standard deviations away from the mean, are removed first before any analysis. For the SPT data of Site 2, as shown in Figure 5(b), there are gaps which are a few multiples of the spacing. Analyses were conducted on the SPT data of equal spacing, and the remaining data were discarded (as indicated in Figure 5b).



(a) Site 1 (b) Site 2

Figure 4. Plots of CPT data

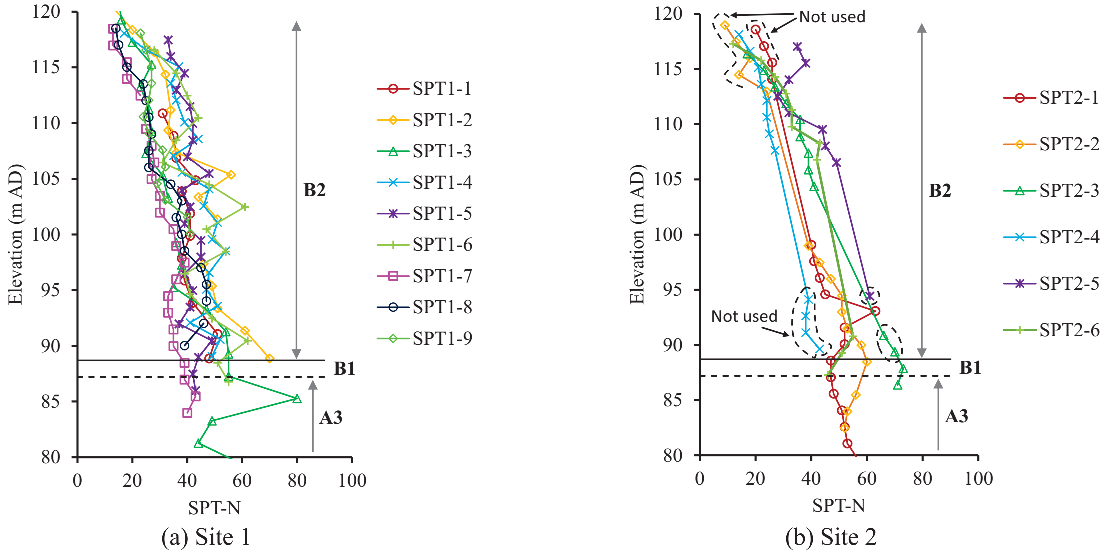


Figure 5. Plots of SPT data

4 Spatial variability analysis

4.1 Methodology

Various methods are available to estimate the SoF (Cami et al. 2020). The simplest and most commonly used approach is to estimate the SoF by fitting the theoretical correlation model to the experimental correlation function (e.g., Lloret-Cabot et al. 2014). The autocorrelation function ρ_k at lag k (spacings) for the CPT and SPT data can be determined by (e.g., Dasaka and Zhang, 2012)

$$\rho_k = \frac{\frac{1}{N-k-1}\sum_{i=1}^{N-k}\left(X_i - \bar{X}\right)\left(X_{i+k} - \bar{X}\right)}{\frac{1}{N-1}\sum_{i=1}^{N}\left(X_i - \bar{X}\right)^2} \quad (1)$$

where N is the total number of data points available, X_i and X_{i+k} are the values of the variable at points i and $i + k$ respectively; and $\bar{x}$ is the mean value of the variable.

There are several theoretical correlation models (e.g., Vanmarcke, 1983; Lloret-Cabot et al. 2014), among them the Markov correlation model is most commonly used (Cami et al., 2020). Hence, the obtained autocorrelation functions are fitted by the theoretical Markov correlation model

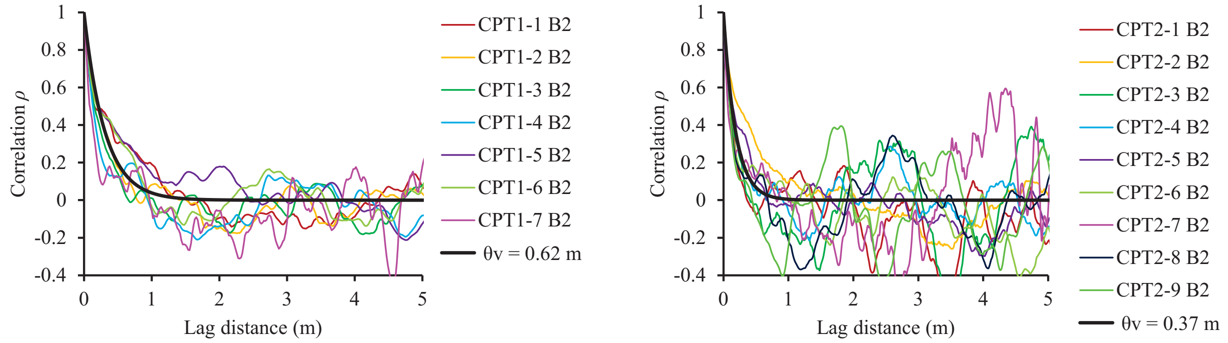
$$\rho(\tau) = e^{-\frac{2|\tau|}{\theta}} \quad (2)$$

where τ denotes the absolute distance between two points, and θ denotes the correlation distance.

4.2 Results and Discussions

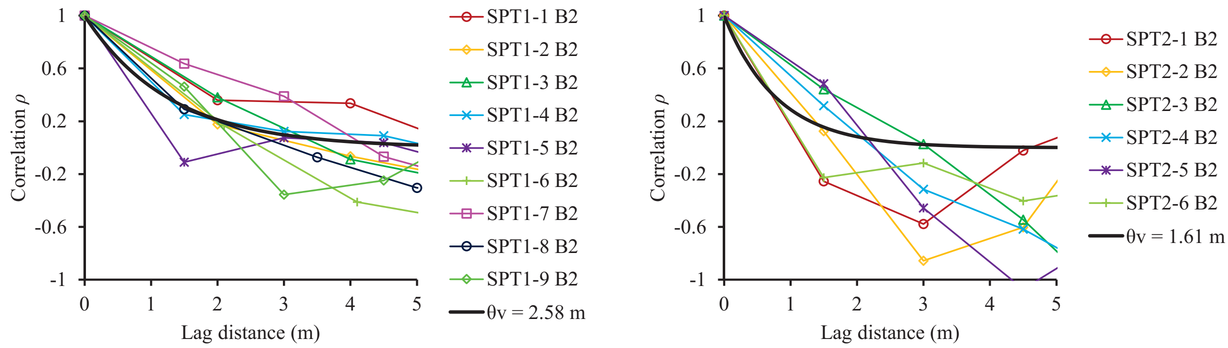
The spatial variability analysis results are shown in Figures 6 and 7 and summarised in Tables 1 and 2. Based on CPT cone resistance data, the mean and standard deviation of vertical scale of fluctuation (θ_v) for Site 1 is 0.62 ± 0.26 m, and for Site 2 is 0.37 ± 0.17 m. Based on SPT, the θ_v for Site 1 is 2.58 ± 0.87 m, and for Site 2 is 1.61 ± 0.48. The CPT at Site 2 were generally terminated at shallower depth than at Site 1, as shown in Figure 4. Similarly, Figure 5 shows that Site 2 has less SPT data compared to Site 1. The θ_v is consistently greater in Site 1 than Site 2 from CPT and SPT. The difference in θ_v for these two sites may be partially attributed to the difference in data sources, and may also be due to the distance between sites, though only 500m apart. If these two sites are combined, the mean and standard deviation of θ_v would be 0.48 ± 0.24m from CPT, and 2.26 ± 0.88m from SPT. The spacing of CPT in this study is 0.02m, which is much lower than the calculated θ_v. Hence, the analysis results from CPT can be viewed as accurate. The spacing of SPT is 1.5 m or 2 m, which is comparable to the calculated θ_v. Therefore, the accuracy of θ_v from SPT is questionable.

According to Jaksa et al. (1999), the stiff overconsolidated clay in Adelaide, Australia, known as Keswick Clay, is remarkably similar to London Clay in terms of geotechnical properties. The θ_v reported based on CPT was 0.06 to 0.24 m with a mean of 0.15 m and COV of 30%. The θ_v for London Clay from this study with CPT would be 0.24 to 1.01 m with a mean of 0.48 m and COV of 50%, which are higher than Keswick Clay. Cami et al. (2020) reported that the θ_v for most soils is less than 3m. The θ_v from this study falls within this range. However, this study highlights that θ_v from CPT can be significantly lower than θ_v from SPT even for the same site. Hence, spacing of the data is critical information for interpreting θ_v, and CPT is preferable where possible.



(a) Site 1 (b) Site 2

Figure 6. Analysis results from CPT data



(a) Site 1 (b) Site 2

Figure 7. Analysis results from SPT data

Table 1. Vertical scales of fluctuation (θ_v) from CPT and SPT for London Clay

Site 1				Site 2			
from CPT tests		from SPT tests		from CPT tests		from SPT tests	
#	θ_v (m)	#	θ_v (m)	#	θ_v (m)	#	θ_v (m)
CPT1-1	0.84	SPT1-1	3.99	CPT2-1	0.27	SPT2-1	NA*
CPT1-2	0.56	SPT1-2	2.01	CPT2-2	0.79	SPT2-2	0.96
CPT1-3	0.46	SPT1-3	2.82	CPT2-3	0.28	SPT2-3	2.12
CPT1-4	0.41	SPT1-4	2.34	CPT2-4	0.34	SPT2-4	1.60
CPT1-5	1.01	SPT1-5	NA*	CPT2-5	0.48	SPT2-5	1.77
CPT1-6	0.72	SPT1-6	1.66	CPT2-6	0.34	SPT2-6	NA*
CPT1-7	0.30	SPT1-7	3.78	CPT2-7	0.33		
		SPT1-8	1.98	CPT2-8	0.29	Mean =	1.61
Mean =	0.62	SPT1-9	2.05	CPT2-9	0.24	Stdev =	0.48
Stdev =	0.26					COV =	30%
COV =	41%	Mean =	2.58	Mean =	0.37		
		Stdev =	0.87	Stdev =	0.17		
		COV =	34%	COV =	46%		

* Excluded in the calculation of mean and standard deviation

London Clay was deposited during Ypresian (from 47.8 Ma to 56.0 Ma), the oldest age of the Eocene. The thickness of London Clay is up to 150m in eastern part of the London Basin (King, 1981). Assuming that 150m of London Clay was deposited at a uniform rate between 47.8 Ma and 56.0 Ma, deposition of 1m London Clay could have required about 54,700 years. The mean value of θ_v from the CPT of the two sites is 0.48 m, which required more than 26,000 years. The origin of spatial variability is often attributed to geological processes occurring in the deposition of soil layers (Phoon & Kulhawy, 1999). A classical explanation is that a large-scale variation may occur due to seasonal changes in the deposition, whereas a small-scale variation may be due to local hydrodynamic processes, e.g., eddy currents (e.g., De Gast et al., 2021). As tens of thousands of years are required to deposit clay to the thickness of θ_v, the origin of spatial variability might not be explained by the seasonal variation or local hydrodynamic processes alone. Within the subdivision B2 of London Clay, as revealed by the moisture content profile in Figure 3, there are weakly discernible sedimentary cycles (Hight et al. 2003), which may be used to explain the spatial variability.

Table 2. Summary of vertical scales of fluctuation for London Clay

Vertical scale of fluctuation, θ_v (m)			
Range	Mean	Standard deviation	Coefficient of variation
0.24 – 1.01	0.48	0.24	50%
0.96 – 3.99	2.26	0.88	39%

5 Conclusions

This paper analysed the vertical scale of fluctuation (SoF) of London Clay using cone penetration test (CPT) and standard penetration test (SPT) data from two sites in central London. The analyses were carried out for subdivision B2 of London Clay according to King (1981)'s classification. The vertical SoF obtained from CPT is 0.24 – 1.01 m with a mean of 0.48m and coefficient of variation (COV) of 50%. The vertical SoF obtained from SPT is 0.96 – 3.99m with a mean of 2.26m and COV of 39%. The SoFs are drastically different, despite the CPT and SPT tests all being carried out in relatively close proximity to each other. The SoF from CPT is considered as more accurate due to the close spacing (0.02 m). The SoF from SPT may not be reliable, as the spacing (≥ 1.5 m) is in the same order of the SoF. Hence, CPT is recommended for site characterisation of SoF. If SPT is used, the SoF may be overestimated. The origin of spatial variability of London Clay may be attributed to sedimentary cycles that could across tens of thousands of years rather than seasonal variations that commonly assumed.

Acknowledgments

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