Vertical spatial variability of over consolidated clays in the UK: geological influence and implications for cutting stability

BGA Annual Conference 2023

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Acknowledgements: This work was funded by the Engineering and Physical Sciences Research Council (EPSRC) through the ACHILLES programme grant (EP/R034575/1). CPT data were provided by HS2 Ltd, In-Situ Site Investigation and the British Geological Survey.

1. Introduction and data acquisition

- High plasticity clay mudrocks are non-uniform and have significant spatial heterogeneity - formed during deposition, diagenesis and weathering[1]. Geotechnical modelling often represents the effects of heterogeneity using simplified models.
- Spatial correlation (θ), of soils is the distance over which soil properties are correlated[2,3]. Quantifying θ allows for probabilistic modelling, which accounts for spatial heterogeneity, to be undertaken.
- CPT data was collected for six UK high plasticity mudrock formations (Figs. 1 and 2); vertical spatial correlation (θ_v) was quantified for these materials and the primary controls on θ_v variations between formations and locations were identified.
- Probabilistic random finite element modelling (REFM) was used to identify the effects of spatial correlation variability on the probability of cutting slope failure (p_f).

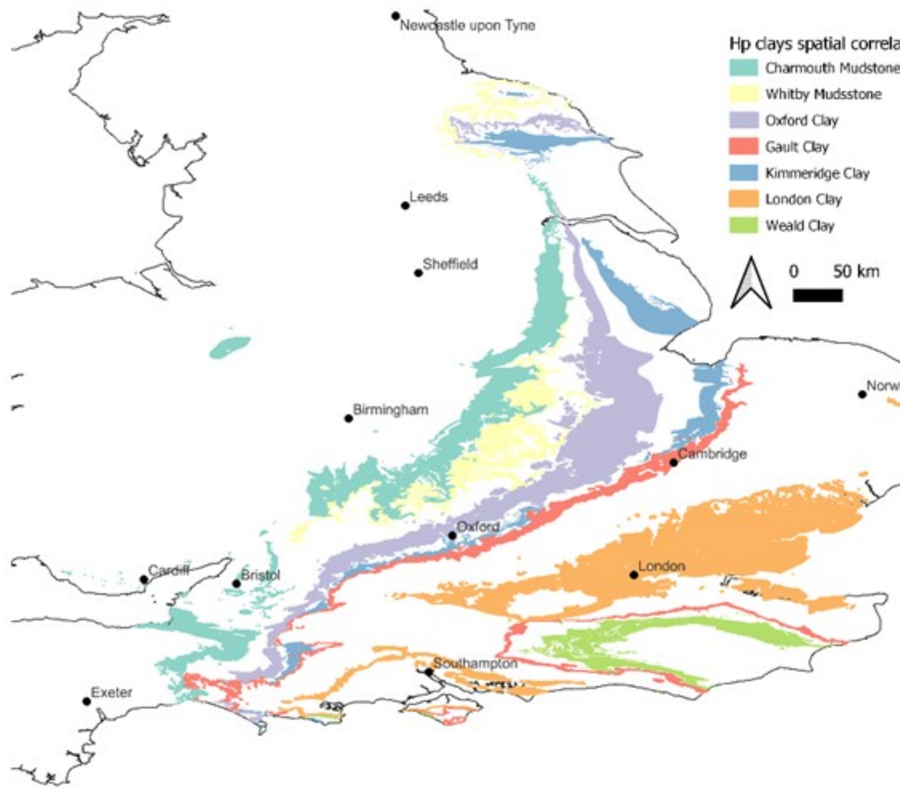


Fig. 2: Locations of UK high plasticity clay formations

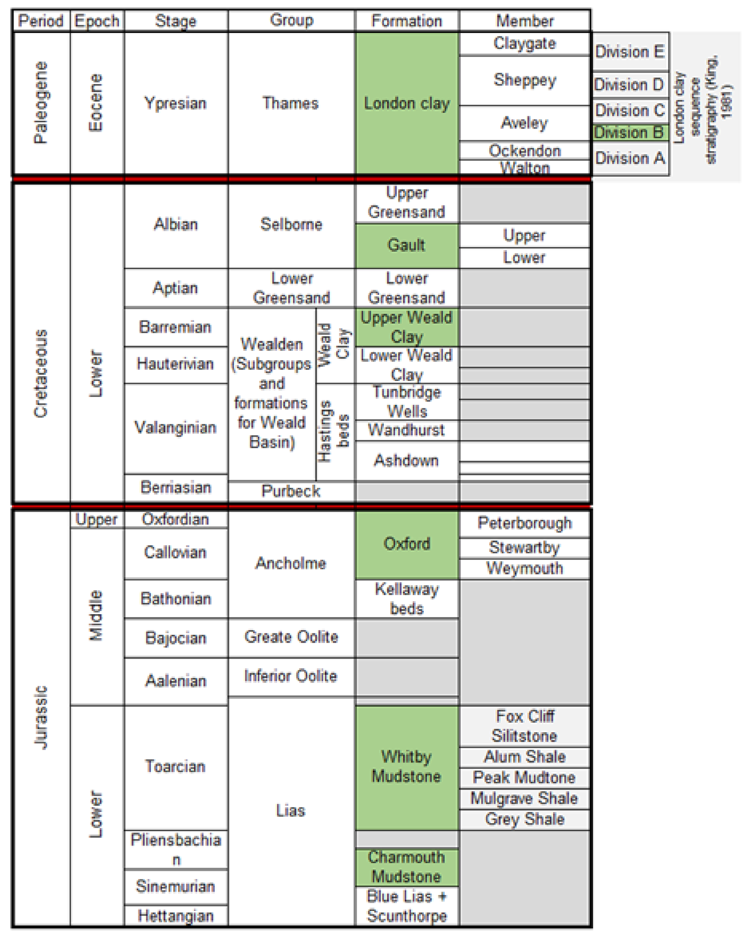


Figure 1: Stratigraphic column showing formations analysed in green. Red zones have been truncated from the column.

2. Spatial Correlation calculation

- θ_v was calculated for CPT tip resistance (q_c) data. Data obtained from 162 CPT tests at 11 sites in 6 formations were analysed.
- Four pre-processing steps were undertaken on each CPT profile. 1) Only CPTs with a lag (Δτ) of 0.01m were used[3,4]; 2) The disturbed near-surface zone, not exceeding 1.5m, was excluded; 3) To ensure material homogeneity, only CPTs with a soil behaviour type index (I_c) Coefficient of variation < 10% were used[3,5]; 4) Linear depth-trend was removed to ensure data stationarity[6] (Fig. 3).

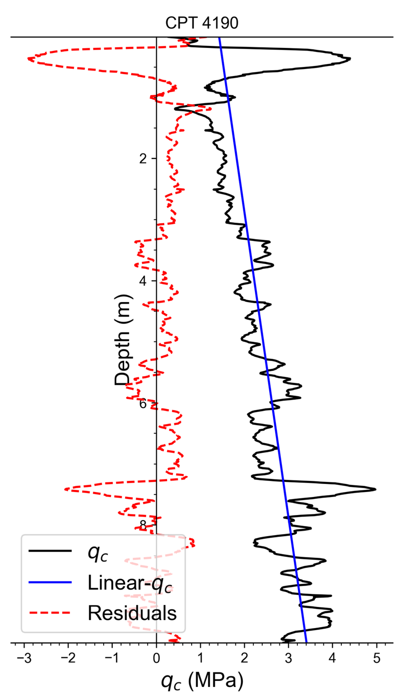
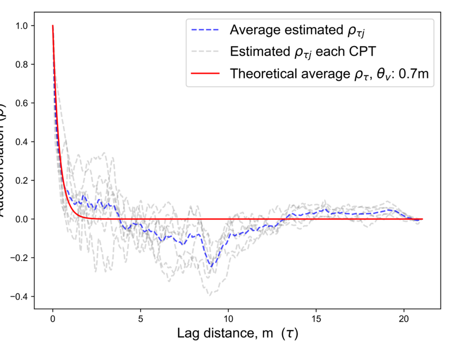


Figure 3: Linear trend removal (blue) from raw CPT data (black) to produce a stationary dataset (red).



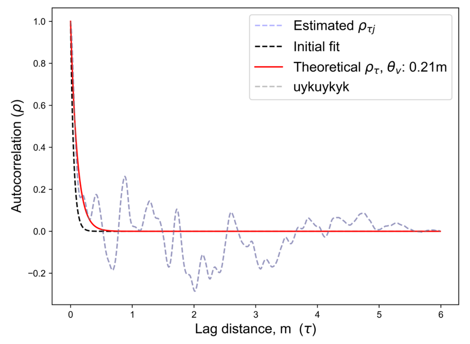


Figure 4: Examples of θ_v fitting. Left: All CPT profiles at site GCC, located in the Gault Clay, Right: an individual CPT profile from the same location.

- Spatial correlation is is equal to the θ_v value which minimises the sum of the square of the errors (Eq. 1) between the theoretical (Eq. 2) and experimental (Eq.3) correlation models[2,4] (Fitting curve is shown as a red line in Fig. 4).

Eq. 1 $\sum_{j=1}^{N}\left(\rho_{\tau j}-\rho_{\tau}\right)^2$ **Eq. 2** $\rho_\tau = \exp\frac{-2|\tau|}{\theta_v}$ **Eq. 3** $\rho_{\tau j} = \sum_{i=1}^{N-j}\frac{w_i w_{i+j}}{w_i^2}$

N = the total number of datapoints in the data series. τ = the distance between two datapoints. w_i and w_{i+j} are the values of the detrended q_c values at datapoints i and i+j, respectively; j = 1,2,..., N/4

3. Spatial Correlation Results

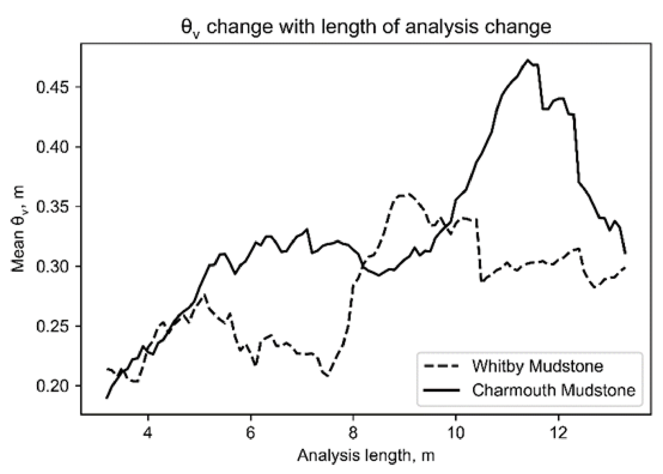


Figure 5: Change in θ_v when material from different depths is included in analysis. The jump in θ_v between 8m—11m is concordant with the transition from weathered to unweathered material identified in borehole logs[11].

- θ_v was found to be higher at depth in all sites where θ_{vf} was calculated for two depth locations, suggesting that materials become more homogenous with depth (Fig. 6).
- In the WHM and CHAM there is a clear distinction between weathered material in the upper 6-8m and unweathered material below (Figs 5 and 6).
- Negative skew of θ_v (Fig. 6) likely due to the presence of variable secondary fabrics within formations, or the differential development of weathering profiles.
- **Due to stratigraphic variation, care should be taken when extrapolating spatial correlation lengths to broader locations .**

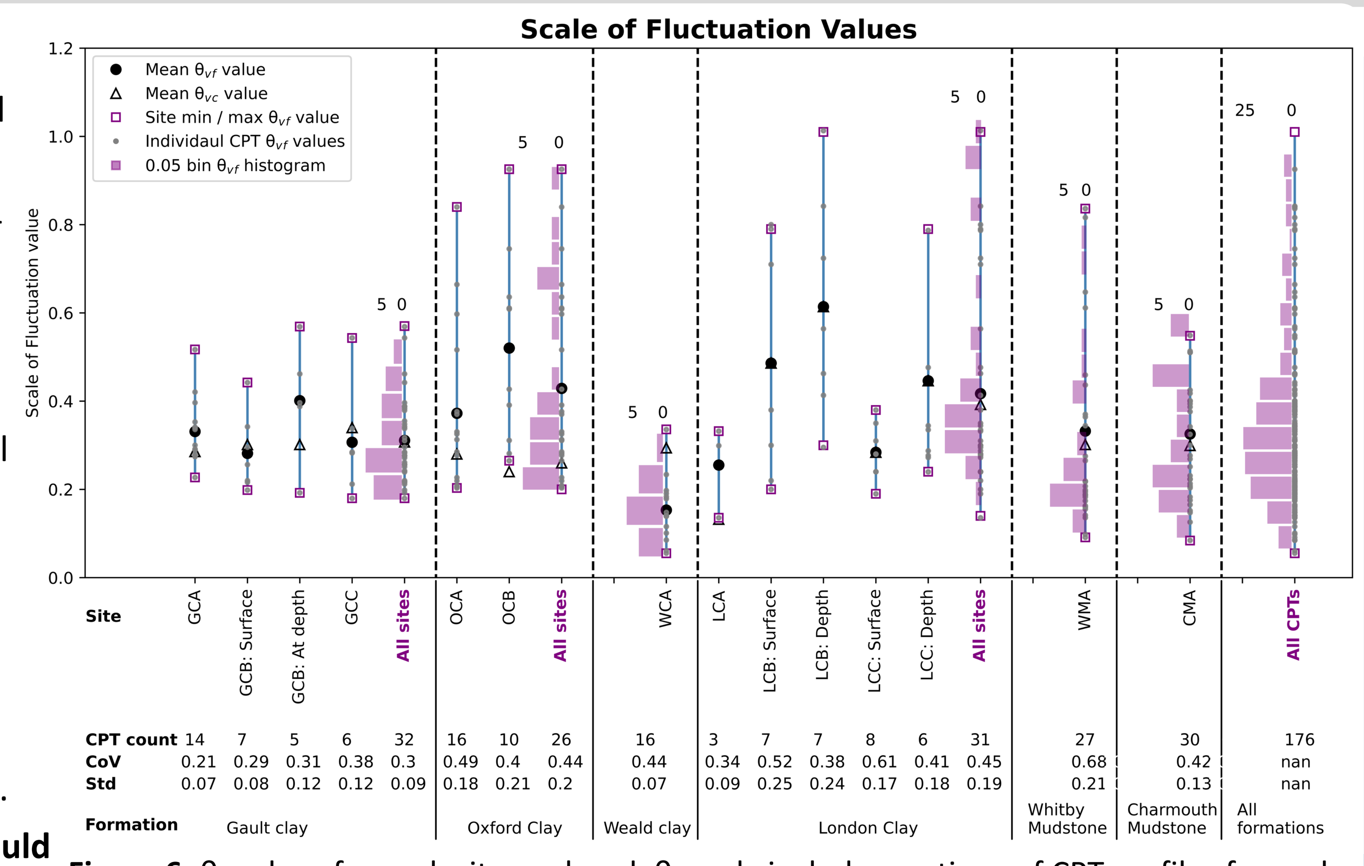


Figure 6: θ_v values for each site analysed. θ_{vc} only includes sections of CPT profiles formed of clay; θ_{vf} values include non-clay material, as classified using the Robertson 1986 method[12]. The distribution of θ_{vf} values calculated for each material is shown in a histogram.

4. RFEM method

- RFEM was undertaken using the software 'MrSlope2d'[8]
- RFEM models complete multiple Monte Carlo simulations to calculate p_f[7,8]; 1000 simulations were run for each scenario. p_f is equal to the proportion of simulations where failure occurs.
- During each Monte Carlo simulation, material properties (Table 1) of individual elements were randomly defined using a log-normally distributed mean and standard deviation, in conjunction with θ_v and θ_h values
- Cutting slopes gradients of 1 in 1 (45°), 1 in 2 (26.6°) and 1 in 3 (18.4°) were modelled.
- θ_v (0.01m—2m) and θ_h (0.2m—20m) were altered between simulation sets to identify the effects of the θ_v differences identified on slope stability. The θ_v value range used covered the range calculated for UK—high plasticity clays.

Table 1: Material properties used during modelling, representing high plasticity clays between peak and fully softened strength. Cohesion and friction angle were varied between models, as a P_f of 0 was calculated for slopes shallower than 1 in 1 for all $\theta_v - \theta_h$ combinations when using the higher cohesion values.

Material	Mean	Coefficient of variation
Friction angle	1 in 1: 22° 1 in 2: 22° 1 in 3: 17°	0.16
Cohesion	1 in 1: 4 kPa 1 in 2: 1 kPa 1 in 3: 1kPa	0.3
Dilation angle	0.1	0 - Deterministic
Unit weight	2,000 Kgm^{-3}	0.03
Elastic mod-	30 MPa	0
Poisson's ratio	0.1	0 - Deterministic

5. Effects of θ on failure surface

- For 1 in 1 slopes, shallow rotational critical slip surfaces (CSS) predominantly developed; CSS' did not develop below slope toes (Fig. 6).
- CSS' became deeper in slopes with shallow gradients and with higher θ_h values. The bases of slip surfaces developed along, or through, weaker bands of material or at contacts between weak and strong zones.
- In models with high θ_v and low θ_h, multiple small near failures developed—with the size constrained by stronger vertical zones (e.g. Fig. 6B) .

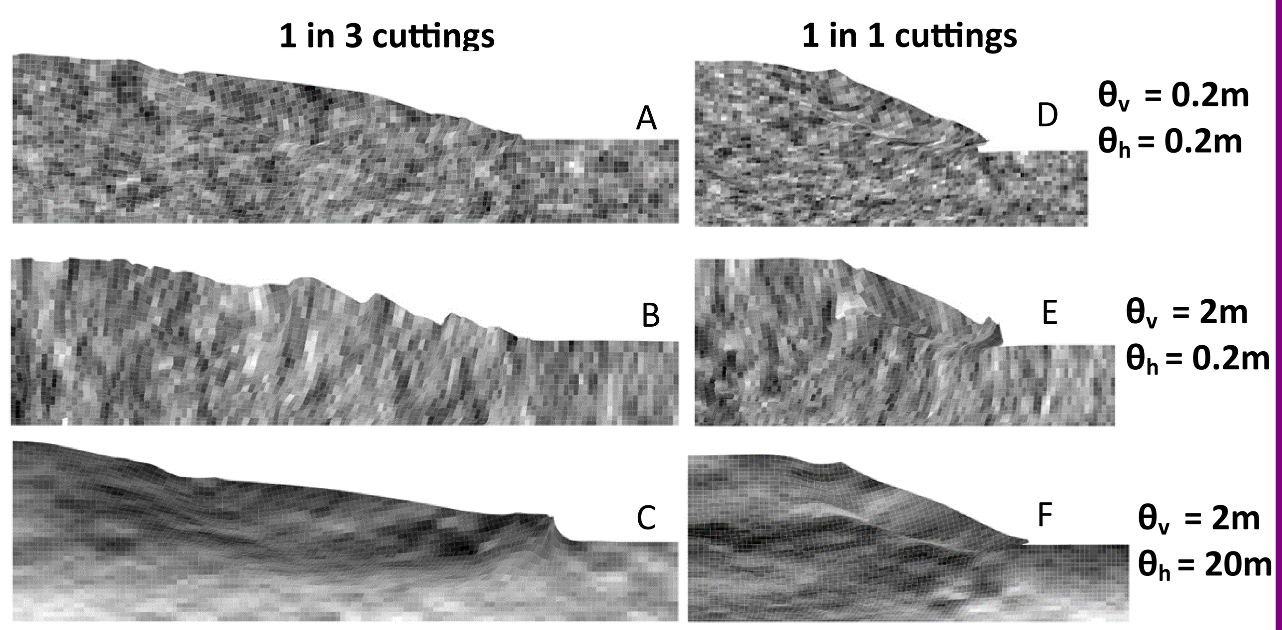


Figure 6: Effect of θ_v—θ_h relationship on slip surface development. Darker elements have stronger material properties; element strength changes in every simulation. 1 in 2 slopes (not shown) showed behaviour consistent with 1 in 3 slopes.

6. Effect of θ_v on p_f

- In 1 in 1 and 1 in 2 slopes peak p_f is associated with the development of the most continuous horizontal planes - which can act as preferential failure surfaces. Similar behaviour is not thought to occur in 1 in 1 cuttings as continuous planes have less influence in narrower, steeper, slopes.
- Relative p_f change , rebased by θ_h max, (Fig. 7) shows that θ_v which causes the highest p_f (worst case θ_v), increases with reductions in slope angle.

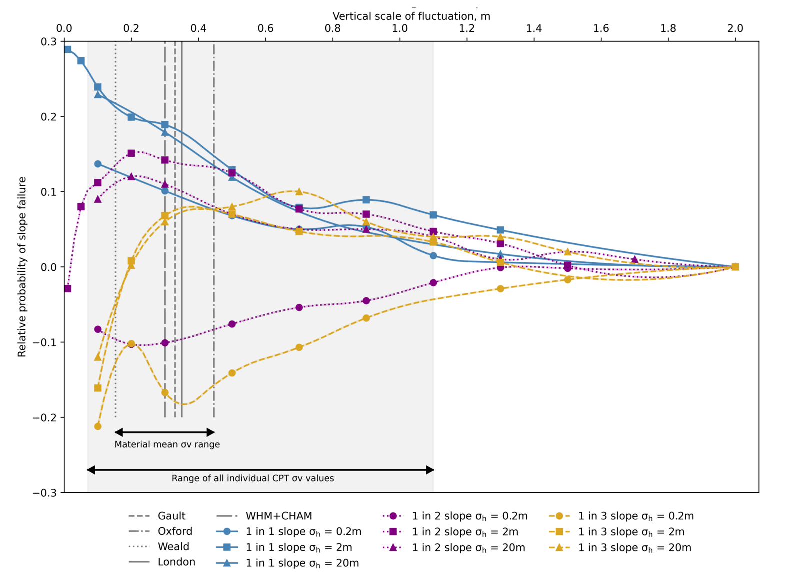


Figure 7: Relative trends in p_f between different slopes. As different material properties were used for different slopes raw p_f values, without rebasing, are not directly comparable—though behaviour trends are.

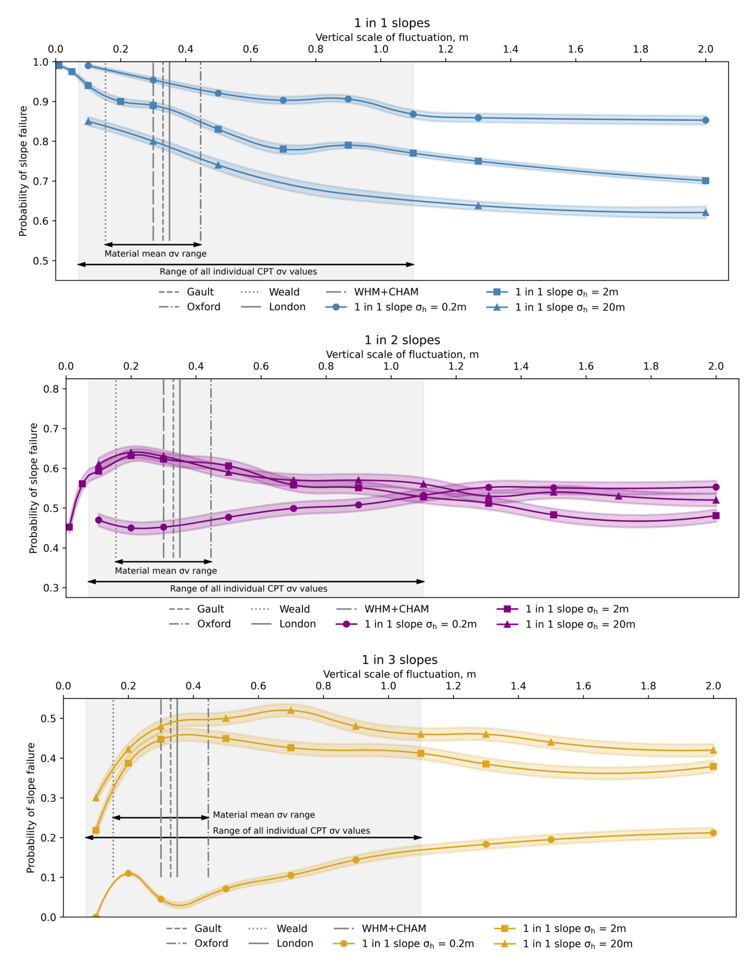


Figure 6: Effects of θ_v and θ_h on probability of slope failure. Error bars show +/- 1 standard deviation.

Given the varying angles of UK infrastructure cuttings, these results indicate the importance of considering spatial variability during the design phase of cuttings in high plasticity clays.

7. Geological context

- θ_v values identified during this study sit towards the lower end of previously recorded θ_v values for clays, which range from 0.05m - 8.6m.
- **θ_v variation between materials and locations is thought to primarily have a lithostratigraphic control, with the additional influence of weathering.**
- For example, θ_{vf} was approximately 40% higher and CoV approximately 20% lower at site OCA in comparison to site OCB. Changes are attributed to differences in member level geology between the two sites. OCB is comprised of Peterborough member clays which have a more variable lithological sequence than the Weymouth Member clays[9] which form material tested at site OCA.
- High CoV values in the Whitby Mudstone are attributed to brecciation and lithorelic development caused by weathering process; high variability is unlikely to have a stratigraphic origin as the Whitby Mudstone has a highly uniform sedimentary sequence[10].

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