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A G-PFEM Analysis of Cone Penetration Testing in Clay Considering Random Destructuration Fields

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Understanding soil structure variability is crucial for geotechnical projects, especially in complex clay formations like London Clay. This study employs the Geotechnical-Particle Finite Element Method (G-PFEM), known for its ability to handle large deformations in insertion problems, while the material response is modeled using an enhanced structured Cam Clay model to investigate the effect of spatial variations in soil structure on cone penetration testing (CPTu) in stiff, overconsolidated London Clay. While it is conceptually recognized that clay structure affects the stress-strain response, our results show that the inherent structure of clay significantly influences the localized shear failure zone around the cone during penetration particularly in soils with structure variations. Using random field theory and Monte Carlo simulation, this study quantifies the spatial variability to refine the predictive accuracy of the G-PFEM model. A vertical scale of fluctuation (SoF) of 0.1 m was initially specified. However, analysis of the CPTu results shows that net cone resistance (q_{net}) maintains an autocorrelation length of approximately 0.1 m, whereas the porewater pressure exhibits a shorter autocorrelation length of about 0.05 m. By incorporating structural variability, the stochastic model effectively captures the inherent heterogeneity of the soil, uncovering spatial variations in stress and porewater pressure redistribution that remain unaccounted for in the deterministic approach. These findings highlight the importance of advanced numerical modeling to capture the complex behavior of clayey soils, thereby improving the interpretation of CPTu results.

Keywords: Probabilistic analysis; Random field; Structure variability; Geotechnical Particle Finite Element Method; numerical analysis.

1. Introduction

Structural variability in soils significantly influences geotechnical behavior, especially in stiff, overconsolidated clays like London Clay. Natural processes (e.g., deposition, consolidation, chemical alterations) produce heterogeneous soil structures that pose challenges for deterministic models, which often fail to capture the complexity of soil response under varying loads, leading to inaccurate geotechnical predictions (Gasparre & Coop, 2008).

The Scale of Fluctuation (SoF) is a key parameter for quantifying the spatial variability of soil properties. It defines the distance over which properties remain correlated and is widely used in stochastic modeling for geotechnical analyses (Uzielli *et al.,* 2005). The vertical SoF is often taken to be around 1m in stiff clays (Charlton & Rouainia, 2019). The unique litho-stratigraphic structure of London Clay suggests that its actual SoF may deviate significantly from these generalizations (Wengui *et al*., 2022). Despite the importance of structural variability and its relationship to SoF, limited studies have specifically addressed these aspects for clays using advanced in situ methods such as the cone penetration test (CPTu) (Monforte & Collico, 2024; Uzielli *et al*., 2005)

This study aims to bridge this gap by modeling the structural variability of London Clay, employing an enhanced structured Cam Clay constitutive model in which the effect of structure and structure degradation are captured. The numerical analysis is conducted using the Geotechnical-Particle Finite Element Method (G-PFEM), a robust numerical tool for large deformation geomechanics, coupled with a random field representation of clay structure. The study investigates how structural variability impacts stress distribution, pore pressure development, and cone resistance during CPTu, while also examining the measured SoF in the resulting outputs.

2. Numerical Approach

The G-PFEM is an advanced numerical approach for modeling the interaction between rigid structures and soil masses during penetration processes (Monforte *et al*., 2017a). This study focuses on clayey materials, which behave nearly undrained during CPTu. An effective-stress formulation explicitly solves pore pressure, capturing hydro-mechanical coupling. Field studies show that the vertical SoF for soil parameters is much smaller by several orders of magnitude than the horizontal scale, so we assume an infinite horizontal SoF and only consider vertical variability (Monforte & Collico, 2024).

2.1. *Numerical domain and boundary conditions*

A coupled hydro-mechanical formulation is used for the quasi-static CPTu simulation. The domain is discretized with triangular elements and linear shape functions, necessitating a mixed stabilized approach to address volumetric locking (Monforte *et al.*, 2017b). A two-dimensional axisymmetric model (see Fig. 1a) uses a cone of diameter D =35.7 mm, initially inserted at 3 D, and then pushed at 0.02 m/s into a domain 20 D wide and 45 D high, with drainage at the top and bottom boundaries and a 100 kPa vertical load on the top boundary. Soil self-weight is neglected, and the initial stresses are $\sigma_v = 200$ kPa and $\sigma_h = 200$ kPa for an over consolidation ratio (OCR) of 5.6. The cone resistance is computed by dividing the force on the cone by its projected area, assuming frictionless contact between the cone and the soil.

2.2. *Constitutive model for London Clay*

The enhanced structured Cam Clay model effectively captures both naturally and artificially structured clays, due to its simplicity and its reliance on standard triaxial test parameters (Carbonell *et al.*, 2022). In a large strain elastoplastic framework, the deformation gradient is split into elastic and plastic components. Fig. 1b shows the yield surface in the triaxial $p' - q$ space, along with the plastic variables p_s (unstructured soil preconsolidation pressure), p_t (tensile resistance), and p_m (yield stress in compression, proportional to p_t); the variable ρs, ρt and χt and χs are constitutive parameters that govern how structure in the soil evolves with plastic deformation. The model parameters are based on those obtained by Gonzalez *et al.* (2012), based on laboratory data from Gasparre (2005), and are listed in Table 1. The calibrated stress-strain curve for the reference material of London Clay subunit B2(a), is presented in Fig. 1c. A nonlocal integration regularization technique is used to mitigate mesh dependency during softening, adopting the weighting function proposed by Galavi and Schweiger (2010).

Table 1. Model parameters

Poisson's ratio, v	Slope of the CSL, M	$\rho s = \frac{1+e^0}{\lambda^* - \kappa^*}$	ρt	k	χt	χs	Critical state friction angle, ϕ_{cs} (°)	p_t (kPa)	p_s (kPa)
0.2	0.85	19.0	-15	3	0.7	0	22.5	120	1130

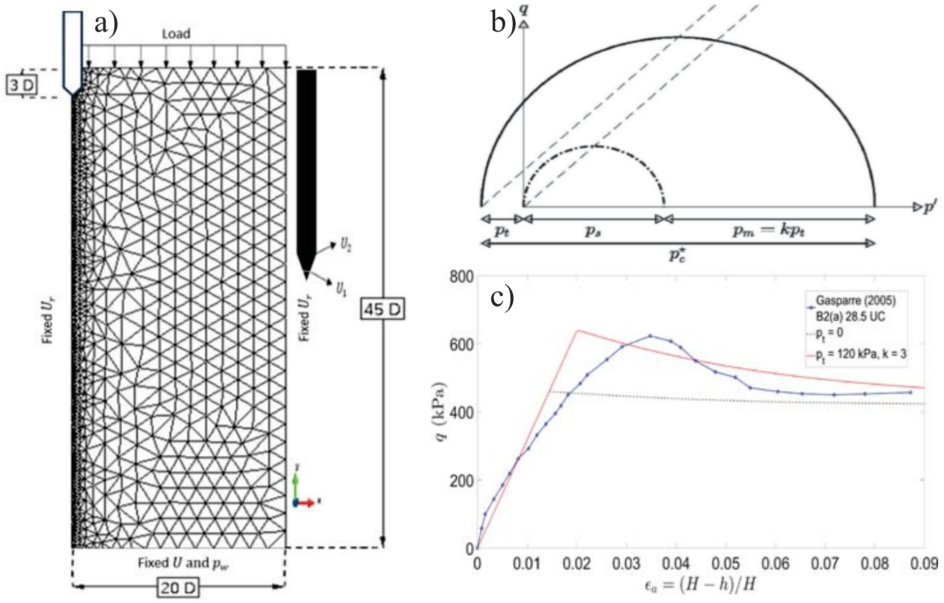

Fig. 1. a) Model geometry, boundary conditions, and initial mesh; b) yield surface in $p' - q$ plane (Carbonell *et al.*, 2022); c) stress-strain $\epsilon_a - q$ with $\epsilon_a = (H - h)/H$ where H and h are the initial and current height of the sample.

2.3. *Random field*

The constitutive parameter k is modeled as a random field in 1D; k is a dimensionless scaling factor that sets the compression-path yield stress p_m in terms of the tensile yield stress p_t, via $p_m = k.p_t$. Given that $k \geq 1$, it is assigned as a shifted lognormal distribution characterized by a mean μ_k, standard deviation σ_k and lower bound $\delta_k = 1$. The spatial correlation of k is defined using a squared exponential covariance function with a vertical SoF $\theta_{\ln(k)}$. The random field is generated using the Karhunen–Loève Expansion (KLE), then mapped to the integration points of the G-PFEM model in an initialization step.

2.4. *Stochastic modeling*

In this study, 100 Monte Carlo simulations are used to characterize the CPTu response. All simulations are conducted with $\mu_k = 2.7$ and $\sigma_k = 0.3$. The potential variability of k was estimated through triaxial calibrations performed on soil samples chosen at depths ranging from 7 m to 38 m. The resulting CoV is 0.11.

3. Results and Discussion

The results are evaluated using net cone resistance $q_{net} = q_t - \sigma_{vo}$ and porewater pressure at the u_1 and u_2 locations and are presented in Fig. 2. For comparison, a reference (black) solution assumes a homogeneous soil.

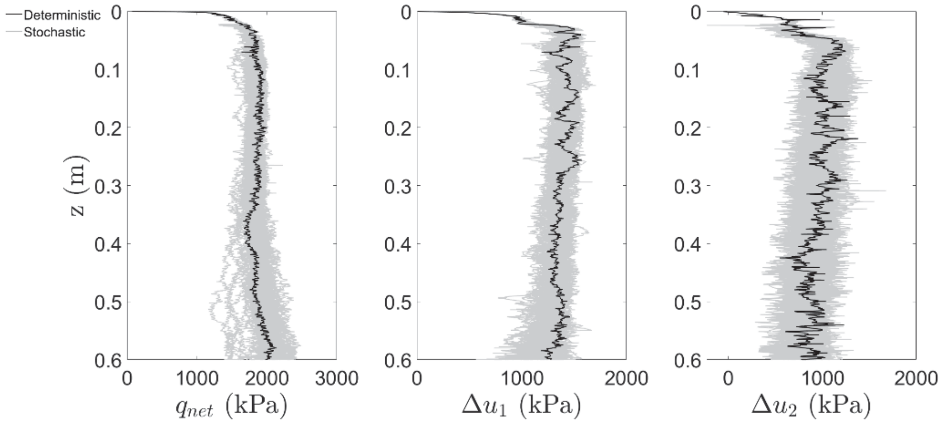

Fig. 2. Simulation results for the deterministic simulation and 100 realizations.

In Fig. 3, the variability in k (see Fig. 3a) influences the destructuration process shown (in Fig. 3b), which in turn causes the porewater pressure contours to narrow (see Fig. 3c), as the cone encounters regions with varying k. Higher k values allow stresses and pressures to extend further into the soil domain, whereas lower k values confine these fields near the cone.

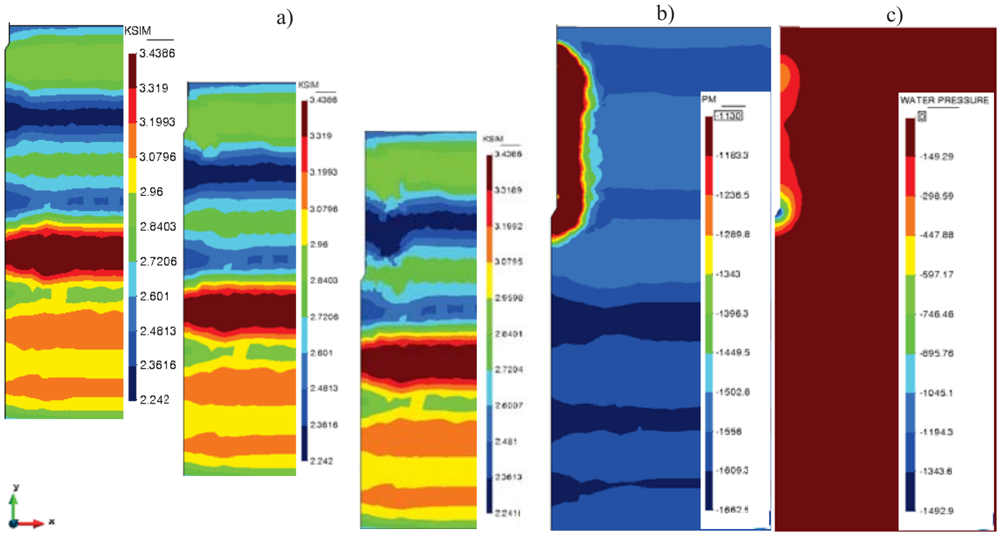

Fig. 3. Contour plots of one random field realization showing: a) the random field of k at 0, 10, and 14 D cone penetration, b) the destructuring process, p_m of the soil around the cone at 14 D and c) the porewater pressure, u_1 at 14 D cone penetration.

Fig. 4 shows the autocorrelation plots for q_{net} and u_1, illustrating the spatial variability from the stochastic simulations. The pore pressure distribution (especially u_1) helps identify lithological changes (Gasparre, 2005), and it is particularly important for analyzing London Clay. The autocorrelation functions $\rho(d)$ begin at 1 for $d = 0$ and decrease with increasing d, indicating diminishing spatial correlation. The fluctuating component was subjected to a trend removal ensuring any systemic depth dependent increase or decrease was taken out. In each subplot the light grey lines represent individual realizations, whereas the dashed black line is the merged average of 100 realizations. An SoF of $\theta_{\ln(k)} = 0.1$ m was prescribed in the random field and the calculated autocorrelation distance from the CPTu responses for q_{net} is 0.1 m (See Fig.4a) which is very close to the prescribed value. However, for u_1, the calculated autocorrelation distance is about half of that, indicating a shorter correlation length in the measured data than prescribed. Field CPTu data in London Clay can exhibit a larger range of vertical SoF values of 0.24–1.01 m (Wengui et al., 2022), likely reflecting real geological layering and site-specific heterogeneities. The authors found that two CPTu locations separated by only 500 m showed different scales of fluctuation, highlighting how local variations within the same formation can affect the measured variability. A study conducted by Jaksa et al., (1999) on stiff, overconsolidated clays reported SoF values in the range of 0.06 m to 0.24 m, which closely aligns with our numerical results. In their conclusions, they noted that the SoF is effectively equivalent to the correlation distance. In our setup, the prescribed SoF of 0.1 m is largely preserved in the final $q$net, whereas the autocorrelation for $u1$ is about half that value.

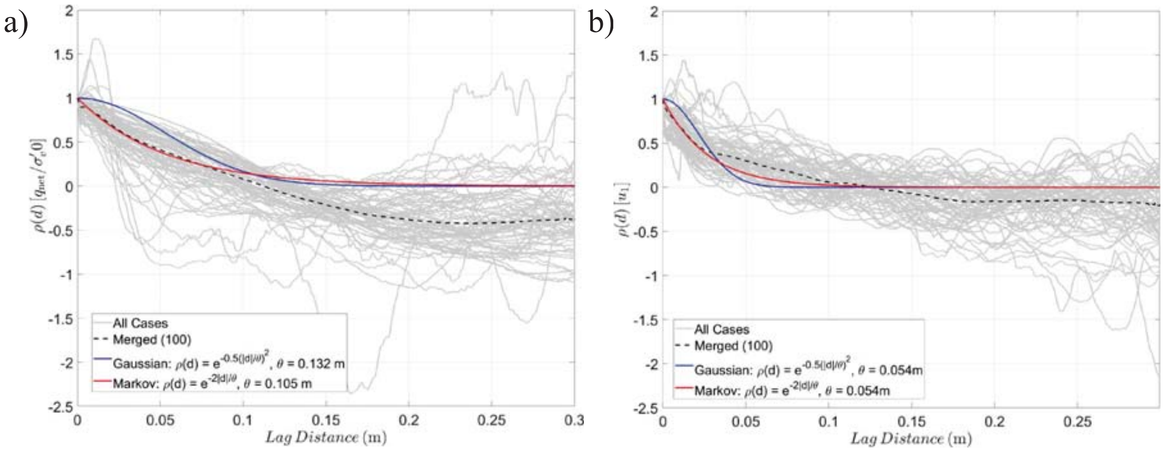

Fig. 4. Spatial autocorrelation function ρ(*d*), where *d* is the lag distance, of a) the normalized cone resistance, adjusted by the in situ vertical effective stress, and b) the porewater pressure at the u_1 location.

4. Conclusion

These results demonstrate that combining an advanced numerical approach (G-PFEM) with a stochastic Cam Clay framework can effectively capture short-range variability in stiff, overconsolidated clays. Our simulations show that the 0.1 m SoF is largely preserved for q_{net}. However, the input autocorrelation function was smooth (Gaussian), but measured CPT autocorrelation was non-smooth. Such findings highlight that while structured clays can exhibit significant variability on a local scale, further research is needed to determine whether this can be accurately assessed or interpreted using current in-situ testing methods.

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