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Assessing the impact of correlated geotechnical properties on the behaviour of retaining structures

Évaluation de l'impact des propriétés géotechniques corrélées sur le comportement des structures de retenue

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ABSTRACT: This study investigates the geotechnical intricacies of Copenhagen's Quaternary upper clay till deposits, characterized as highly over-consolidated and significantly heterogeneous, and their impact on the structural performance of secant pile walls. Through rigorous analysis, 5000 samples were generated using multivariate distribution functions. These functions were developed to probabilistically calibrate the HS-small constitutive model, taking cross correlations into account. Additionally, 5000 more samples were generated assuming independence. These samples serve as the basis for a finite element model, providing crucial data on lateral wall deflections and bending moments. The impact of cross correlations among geotechnical properties on secant pile wall response is evident. The study quantifies this impact, showing a substantial reduction in standard deviation for lateral deflections (about 20%) compared to interdependent samples. The maximum bending moment during the final excavation stage sees a more modest 50% decrease. This study not only sheds light on the importance of considering dependencies among geotechnical properties in deep excavation design but also provides a practical framework for optimizing performance and safety in similar projects.

RÉSUMÉ: Cette étude explore les subtilités géotechniques des dépôts argileux quaternaires à Copenhague, fortement surconsolidés et très hétérogènes, et leur impact sur les performances structurelles des parois moulées. En analysant rigoureusement 5000 échantillons générés par des fonctions de distribution multivariées, le modèle constitutif HS-small a été probabilistiquement calibré en tenant compte des corrélations croisées. Ces échantillons, à la base d'un modèle par éléments finis, fournissent des données clés sur les déformations latérales et les moments de flexion des parois. L'impact des corrélations croisées sur la réponse des parois moulées est mis en évidence, montrant une réduction significative de l'écart type des déformations latérales (environ 20%) par rapport aux échantillons interdépendants. La diminution du moment de flexion maximal lors de la phase finale d'excavation est plus modeste, à hauteur de 50%. Cette étude souligne l'importance de considérer les dépendances entre les propriétés géotechniques dans la conception des excavations profondes, offrant un cadre pratique pour optimiser les performances et la sécurité dans des projets similaires.

Keywords: Multivariate distribution functions; cross correlations; deep excavation design; secant pile walls.

1 INTRODUCTION

Deterministic approaches, which are most commonly employed for geotechnical design, can fail to accurately predict soil structure interaction in complex geotechnical conditions, because they rely on single-value properties. Representing geotechnical properties as probability distribution functions enables the incorporation of inherent uncertainties and variations in a more comprehensive manner. In particular, advanced probabilistic techniques, such as bivariate or multivariate distributions, account for the correlation among geotechnical properties and establish a platform to gauge the potential influence of correlated parameters on structural performance through reliability-based design (RBD) techniques.

In the field of geotechnical engineering, a multitude of multivariate distribution functions have been developed, drawing from both regional and global databases (Ching and Phoon 2012, Liu et al. 2016, Zang et al. 2020). These functions share a common aim: to effectively capture cross correlations among various geotechnical properties. Macroscopic geotechnical properties, such as shear strength, permeability, and stiffness are in fact governed by the same physical parameters and microscopic features, therefore they exhibit inherent interdependencies. Multivariate distribution functions describing these correlations lessen uncertainty, provide a complete overview of overall variations, and assist in developing precise transformation models for particular situations.

Despite the acknowledged correlation among geotechnical properties, a noticeable gap persists in the literature regarding the integration of these correlations into reliability-based design studies for deep excavations, as highlighted in various published studies (Gong et al., 2016; Wang et al., 2020). The majority of these studies have treated geotechnical properties as independent variables, neglecting the intricacies of real-world behaviour or focus solely on specific ones, such as the extensively studied relationship between effective cohesion (c´) and angle of shearing resistance (φ´). This gap is further underscored by the absence of established multivariate distribution functions aimed at calibrating soil constitutive models in a probabilistic manner.

This paper aims to investigate the impact of considering the cross-correlation between different geotechnical properties on the performance of single-anchored secant pile walls embedded in a uniform clay till layer. To achieve this, soil samples were generated based on established multivariate distribution functions developed by Panagiotis et al. (2023) for the Copenhagen upper clay till. These functions aimed to probabilistically calibrate the HS-small constitutive model and were used to explore two scenarios. In the first scenario, samples were generated while considering the observed cross-correlations among geotechnical properties. In the second scenario, the selected geotechnical properties were treated as independent probability density functions, resulting in a correlation matrix being an identity matrix. For each scenario, a total of 5000 generated samples were incorporated into a finite element model (FEM) created in PLAXIS 2D. This model was employed to calculate and compare wall deflections and maximum bending moments at both initial and final excavation stages between the two scenarios. The comparisons were conducted using various statistical measurements, including standard deviation and confidence intervals.

2 METHODOLOGY

2.1 Geology of Copenhagen (clay till dep)

The greater Copenhagen's geology dates to the Paleogene and Quaternary epochs. Thicker glaciers covered the area twice, causing Paleogene deposits (limestone) to be overlaid by glacial deposits. These glacial deposits are categorized into clay, sand, and gravel tills based on their natural moisture content, rather than their grading (Frederiksen et al., 2003). The Quaternary upper clay till in Copenhagen is the focus of this study, which is characterized as a highly over-consolidated (OCR ~ 1-20) low to medium plastic clay (I_p < 15%), with a clay fraction varying from 15% to 30%.

2.2 Multivariate distribution functions

Due to the limited and incomplete database for calibrating the Hardening small-strain stiffness (HS-small) constitutive model, Panagiotis et al. (2023) constructed two distinct multivariate distribution functions: one based on anisotropically consolidated drained/undrained tests and soil classification, and the other on oedometer and soil classification, sharing four common parameters. Geotechnical data from triaxial and oedometer functions were combined based on minimum differences for the common parameter, assuming similar samples with matching stress and index properties. This approach capitalizes on shared characteristics to effectively merge information from the two multivariate functions. The first multivariate distribution function comprised eight parameters (q/p´, OCR, E^{ref}_{50}, e_0, LL, depth, $p´_i$, $p´_{peak}$) and the second comprised seven parameters ($E^{ref}_{oed,u}$, OCR, C_k, e_0, LL, depth, $E^{ref}_{oed,l}$). The correlation matrix after the combination of the two multivariate distribution functions is presented in Table 1.

Table 1. Correlation matrix among the geotechnical properties adopted in this study.

C_{xx}	e_0	q/p´	E^{ref}_{50}	OCR	C_k	$E^{ref}_{oed,l}$
e_0	1.00	-0.22	-0.92	-0.13	0.54	-0.41
q/p´		1.00	0.42	0.52	-0.08	-0.22
E^{ref}_{50}			1.00	0.36	-0.43	0,34
OCR	Symmetric			1.00	0.16	0.03
C_k					1.00	-0.32
$E^{ref}_{oed,l}$						1.00

Initially, 5000 samples were generated using multivariate distribution functions that considered cross correlations, while an additional 5000 samples were generated assuming independence. These samples were imported into the FEM model developed on PLAXIS 2D and lateral wall deflections and bending moments were calculated. The generated samples used for the analyses on the two scenarios are illustrated in Figure 1.

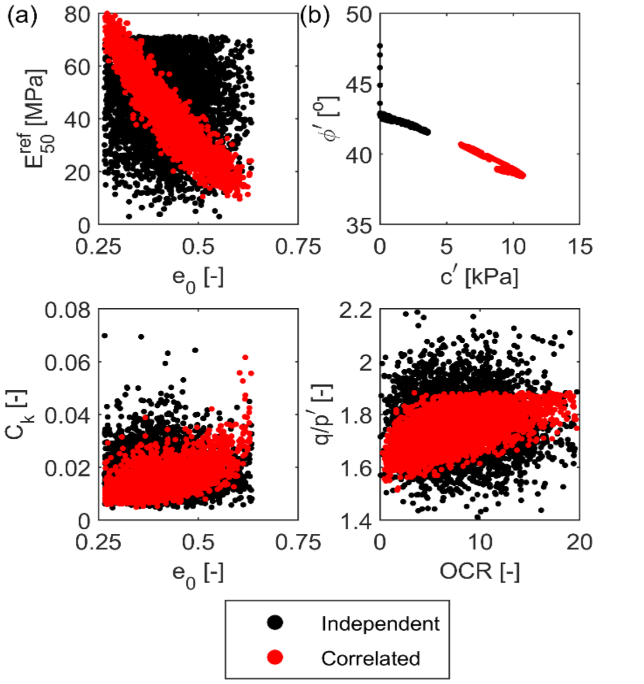

Figure 1. Scatter plots of generated samples implemented in PLAXIS 2D for the two scenarios.

2.3 Design of secant pile walls

The deep excavation analyzed in this study was embedded within Copenhagen's clay till unit, supported by 15m long secant pile walls and one row of anchors. Secant pile walls were designed according to free earth support method. A schematic view of the deep excavation with the excavation characteristics is illustrated in Figure 2.

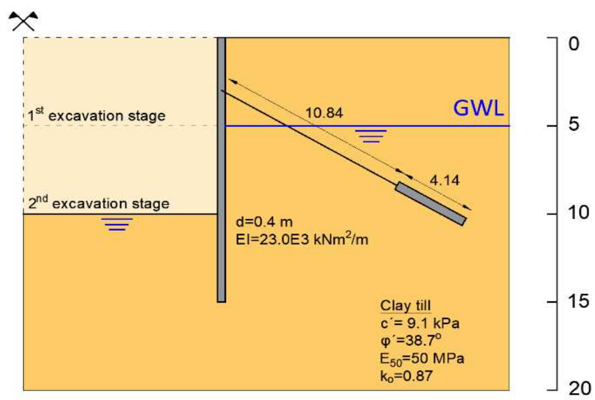

Figure 2. Cross section of the deep excavation analyzed in this study.

It is important to highlight that a c-φ´ reduction analysis was conducted on the developed finite element model in PLAXIS 2D. This was done to ensure that the design of the deep excavation was not overly conservative, resulting in a safety factor of approximately one. This decision was made because our objective was to assess the impact of cross correlations among geotechnical properties on an excavation designed to its limit. The construction sequence of the modelled deep excavation consisted of:

Stage 1: Wall installation
Stage 2: Excavation stage 1 (from +0 to -5.00m)
Stage 3: Anchor activation (-3.00 m)
Stage 4: Ground Water Lowering (from -5.00 to -10.00m)
Stage 5: Final excavation stage (from -5.00 to -10.00m)

3 RESULTS

The lateral wall deflections and bending moments during both the initial and final excavation stages are depicted in Figure 3 and Figure 4, respectively. It is evident that the variability in the response of the secant pile wall is consistently reduced when cross correlations among the geotechnical properties are taken into account. To quantitatively assess the impact of considering cross correlations, the standard deviations of the maximum lateral wall deflections and bending moments were estimated and are presented in Table 2.

Table 2. Standard deviations of the maximum lateral deflections and bending moments for two scenarios during the first and last excavation stage. Confidence intervals (95%) are displayed in parentheses (Lower-Upper bound).

Stage	1^{st} Exc. stage	Final exc. stage
Maximum lateral deflections [mm]		
Independent	23.7 (45.75-47.43)	25.8 (48.55-50.38)
Correlated	5.1 (19.10-19.45)	5.5 (23.47-23.85)
Maximum bending moment [kNm/m]		
Independent	28.5 (70.61-72.63)	12.8 (86.51-87.93)
Correlated	7.3 (30.30-30.79)	6.8 (65.57-66.12)

The most significant reduction in standard deviation was observed in lateral wall deflections, where it decreased to approximately 20%, equivalent to a five-fold decrease compared to samples with correlated properties. In contrast, the reduction in standard deviation for maximum bending moments during the final excavation stage was 50%, indicating a two-fold decrease. When confidence intervals are utilized to determine the required reinforcement, it becomes evident that the required reinforcement area is reduced by 33% when considering correlations. This reduction, in turn, leads to significant reductions in CO2-eq emissions.

4 CONCLUSIONS

In this study, an investigation was conducted into the effect of cross correlations among geotechnical parameters on the structural performance of secant pile walls, with a specific focus on the Copenhagen Quaternary upper clay till. The construction sequence of a deep excavation was simulated considering wall installation, excavation stages, anchor activation, and groundwater lowering.

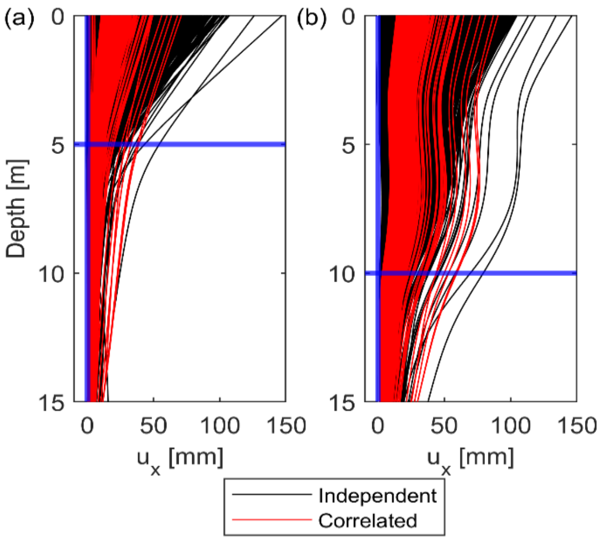

Figure 3. Lateral wall deflections with respect to depth for the two scenarios during the: (a) first excavation stage and (b) final excavation stage.

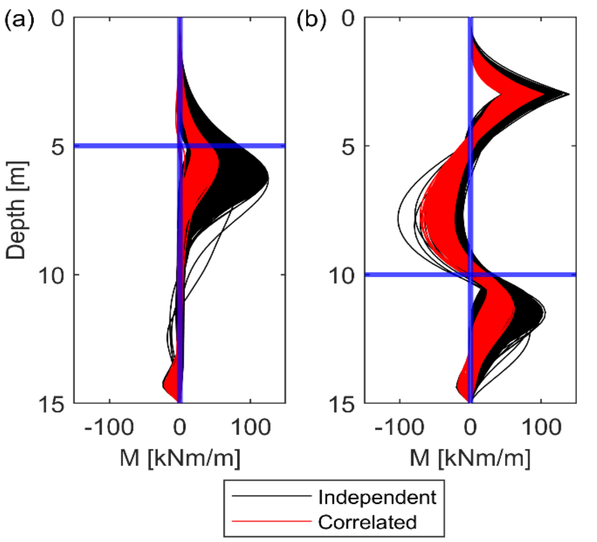

Figure 4. Bending moments with respect to depth for the two scenarios during the: (a) first excavation stage and (b) final excavation stage.

PLAXIS 2D numerical analyses were performed using 5000 samples generated under the consideration of cross correlations, and an additional 5000 samples assuming independent distributions. Lateral wall deflections and bending moments were derived showing a remarkable reduction in variability in the response of the secant pile wall, particularly in lateral wall deflections, when cross correlations were considered. This was quantified by estimating the standard deviations of maximum lateral wall deflections and bending moments, revealing a substantial reduction in standard deviation for lateral deflections of samples having cross correlated properties. Overall, this study highlights the significance of considering dependencies among geotechnical properties in the design and analysis of deep excavations supported by secant pile walls.

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