Proc. of the 9th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Zhongqiang Liu, Jian Dai and Kate Robinson
Published by Research Publishing, Singapore.
doi: 10.3850/GRF-25280825_isgsr-143-P302-cd

AN INVESTIGATION OF PROBABILISTIC STRATIFICATION MODELS FOR ASSESSING DEEP EXCAVATIONS IN URBAN ENVIRONMENTS

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Abstract

Despite the significant uncertainties inherent in geotechnical design and construction, the field predominantly relies on deterministic analyses. To address this limitation, the probabilistic-digital-twin framework has the potential to systematically integrate probabilistic methods into geotechnical design and construction. The framework can explicitly account for uncertainties which is relevant to ensure both safety and efficiency of design and construction. It does require realistic probabilistic models of the geological and geotechnical properties at a site. Recent probabilistic approaches in subsoil models have focused mostly on incorporating spatial variability of soil properties without addressing the significant uncertainties associated with soil stratification. The objective of our work is to develop methods for incorporating uncertainty in soil stratification into geotechnical analysis. In this paper, we investigate the effect of such an uncertainty assessment in a case study involving the construction of a subway station. We focus on the settlements induced by the deep excavations, which can impact neighboring buildings and are thus of particular interest in urban environments. The results demonstrate that stratification uncertainty does significantly impact the predicted settlements and hence the optimal design.

Keywords: deep excavations in urban environments, probabilistic modeling, geotechnical design and construction.

1. Introduction

Even though the Digital Twin (DT) framework is seen as a promising solution to the challenges faced by the construction industry, its broader application in geotechnical design and construction remains limited (Cotoarbă et al., 2024). Phoon et al. (2022a) show that for the successful usage of the DT framework in this field, it should be tailored to specific challenges, such as sparse, incomplete, and low-quality data originating from multiple sources. However, the traditional DT approach assumes that complete knowledge of the physical reality is available, which ignores the presence of uncertainties. This is especially critical in geotechnical engineering, where modeling and prediction uncertainties are inherently high, systematic, complex and correlated (Goulet and Smith, 2013; Phoon et al., 2022b). As a result, the traditional DT framework might fail to accurately capture and predict real-world geotechnical behavior.

To address these limitations, in (Cotoarbă et al., 2024) we propose a Probabilistic Digital Twin (PDT) framework tailored to geotechnical design and construction. The PDT extends the traditional digital twin by systematically incorporating all sources of uncertainty and propagating them throughout the design-construction-operation process. This approach draws inspiration from methodologies in other industries (Agrell et al., 2023; Chaudhuri et al., 2023; Kapteyn et al., 2021; Kochunas and Huan, 2021; Nath and Mahadevan, 2022). In (Cotoarbă et al., 2024) we demonstrate by application to a highway construction project how the PDT can leverage new information to reduce uncertainties in behavioral predictions and support improved decision-making.

The PDT offers a framework to integrate probabilistic methods into geotechnical design and construction in a field that still predominantly relies on deterministic analysis. This integration is particularly interesting for deep excavations in urban environments, where excavation-induced soil settlements will affect neighboring buildings if not managed appropriately. To ensure a safe and efficient design under such conditions, explicitly addressing uncertainties is essential. Recent probabilistic approaches to this challenge have primarily focused on probabilistic subsoil models that incorporate spatial variability of soil properties while assuming constant soil stratification boundaries. Traditional subsoil models do not include the uncertainties associated with soil stratification, which might limit the accuracy of behavior predictions.

The objective of this paper is to describe and evaluate methods for incorporating uncertainty in soil stratification into geotechnical analyses. This will improve the understanding of which aspects of probabilistic subsoil modeling are relevant and should further be included in the PDT framework. In this paper, we compare (1) traditional subsoil models with constant soil stratification and soil properties (see Fig. 1a) with (2) probabilistic subsoil models with uncertainty in soil stratification and deterministic soil properties (see Fig. 1b).

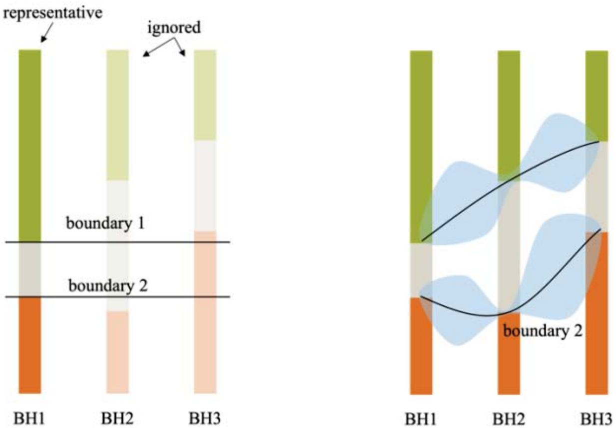

Figure 1. Example subsoil Model with a) constant soil stratification and soil properties; and b) uncertainty in soil stratification and deterministic soil properties;

2. Methodology

The 3D subsoil model is developed using a surface-based modeling approach. This is a method in which layers are identified across borehole soundings to obtain interpolation points. Then, we use Gaussian process regression to generate surface functions that fit the observed data and, thus, get a probabilistic description of soil stratification boundaries. As a result, for each layer, we obtain a probabilistic description by its mean and correlation function. For finite element (FE) analysis, the 3D model is intersected along a plane at the cross-section of interest to obtain a 2D representation. The probabilistic model derived for the case study is illustrated in Fig. 2b, including the 95% confidence interval around the expected layer boundaries. Using this probabilistic framework, 100 distinct 2D subsoil models with varying boundary conditions are generated. FE is performed for each sample, and then the results can be aggregated to obtain a probabilistic prediction of the quantities of interest. Each sample analysis has a computational time of ~3 minutes for this case. The FE analysis is performed in Plaxis 2D with PLAXIS Remote Scripting in Python. For a detailed description of the implementation, we refer to (Karadeniz 2024).

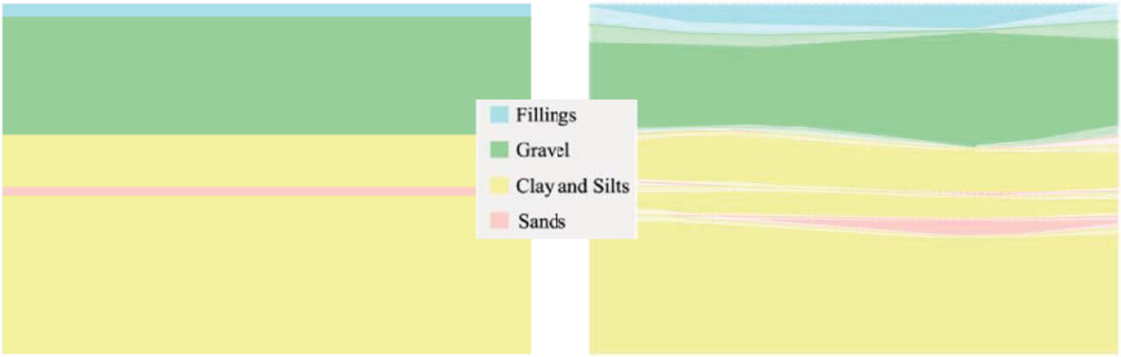

Figure 2. Comparison of two approaches to subsoil modelling for the Munich Case Study with: (a) a deterministic 2D subsoil model as used in the original analysis, which presents fixedsoil stratification, and (b) a probabilistic subsoil model that highlights uncertainty in soil stratification with the 95th percentile layer boundaries around the expected soil interfaces.

3. Case Study

3.1. Project

This case study is derived from Pelz (2010) and considers the construction of a subway station in Munich, Germany, which was completed in 2010. The station was built using the cut-and-cover method and has a total length of 202 m, an excavation depth of 15.9 m, and an embedment depth of 7.6 m.

The focus of this study is limited to cross-section 3-3, for which inclinometer measurements were recorded during construction. We refer to the work of Pelz (2010) for detailed dimensions and a visualization of the cross-section.

For this investigation, we consider on hypothetical loading scenario with a 2-story building with rigid foundation adjacent to the excavation site.

3.2. Geological Conditions

The basis for the model of the on-site geological conditions are borehole soundings. The data for this case study is publicly available through the Bavarian State Office for the Environment and stored in the UmweltAtlas database (Bayerisches Landesamt Für Umwelt, Augsburg, Germany). From this database, we extracted six borehole soundings in the proximity of the construction site.

In the borehole soundings, four soil types are identified, which are typical for Munich: fillings, quaternary gravel, tertiary clays and silts, and tertiary sands. To model the soil types in the FE analysis, we used the *Hardening-Soil Model* and *Hardening-Soil Model with Small-Strain Stiffness*. We us the input soil parameters, orginally obtained by Pelz (2010). They analyzed soil samples and validating them with inclinometer measurements of wall displacements recorded during construction.

3.3. Construction Phases

To reflect the construction process of an excavation pit in urban environments in an FE analysis, the construction is divided into 18 stages. From these, we present results for two states: (1) Strut Activation: Installation and activation of struts (see Fig. 3a) and (2) Strut Removal: Removal of the struts after construction of the bottom slab (see Fig. 3b).

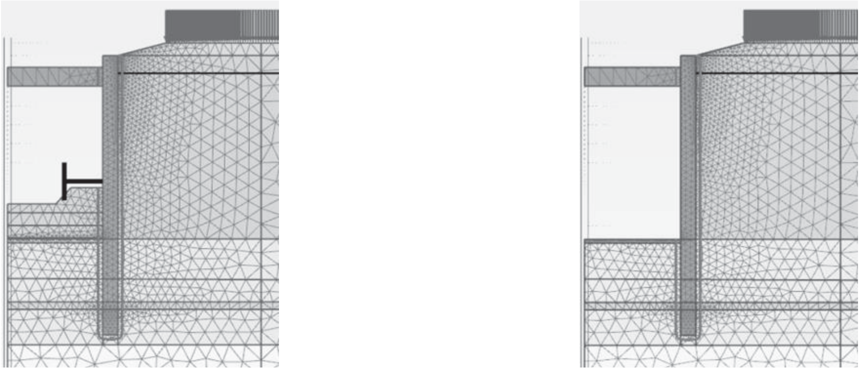

Figure 3. The finite element model for the deterministic subsoil model of the two considered phases: a) Installation and activation of struts; b) Construction of bottom slab and strut removal;

4. Results

Fig. 4 shows wall deflection profiles along the right side of the excavation pit during the two considered construction phases, analyzed using deterministic and probabilistic approaches. While both methods demonstrate consistent overall behavior, with maximum deflection occurring at the midpoint of the wall, the uncertainty range is not centered on the deterministic estimation. The deterministic analysis results fall near the lower bound of the probabilistic range. This shows how the incorporation of more realistic soil profile variations leads to different predicted behavioral patterns. The removal of the temporary strut results in increased wall deflections, as expected, given its role in providing structural support during construction. Interestingly, the soil response variability also increased after strut removal, highlighting that the impact of soil stratification uncertainty varies at different construction stages.

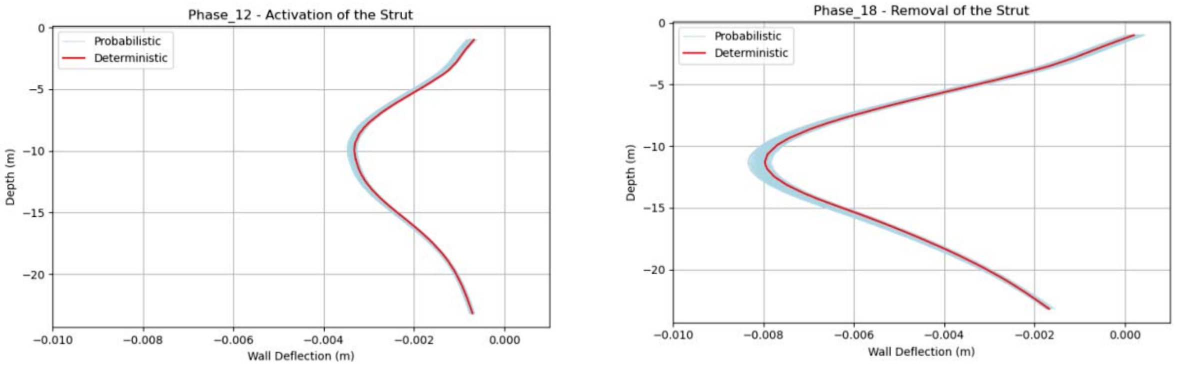

Figure 4. Horizontal wall movements for both phases on the right side of the excavation pit

Fig. 5 presents the ground settlement profiles along the right side of the excavation pit for the same construction phases. Both deterministic and probabilistic approaches show similar behavioral trends, with deeper settlements occurring closer to the wall. Maximum settlements are prediceted in the final phase following strut removal. While the strut removal significantly affects deflections, the settlement variability remains consistently around 10%. However, compared to the wall deflection analysis, the probabilistic approach revealed considerable variability in settlement predictions for both construction phases, highlighting the influence of more realistic soil stratification models on the predicted ground response.

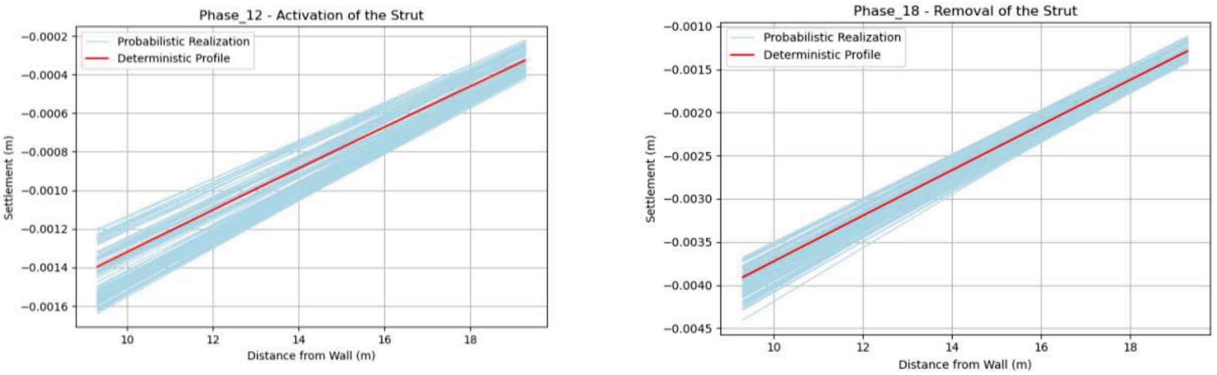

Figure 5. Ground settlements for both phases on the right side of the excavation pit

5. Conclusion and Outlook

The results demonstrate that incorporating soil stratification uncertainty significantly influences the geotechnical analysis of urban deep excavations. The impact of this influence varies substantially across principal parameters and construction stages. As this study represents the first systematic investigation of probabilistic soil stratification effects on the analysis of urban deep excavations, further research is needed to fully understand its implications. Future investigation will combine the variability in soil properties with the presented stochastic subsoil stratification model. These investigations will enhance our understanding of the strengths and limitations of a range of uncertainty modeling strategies and their potential applications within a probabilistic-digital-twin framework.

Acknowledgment

This research is supported by the TUM Georg Nemetschek Institute Artificial Intelligence for the Built World.

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