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PROGNOSIS OF DISCRETE LAYER BOUNDARIES FOR SYNTHETIC GEOLOGICAL MODELS AND THEIR INFLUENCE ON GEOTECHNICAL STRUCTURES

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Considering related subsoil uncertainties in geotechnical analysis is a key factor for robust and sustainable designs as the subsoil is the main load-bearing domain. Consequently, a holistic framework is proposed that integrates a conceptual geological model, stochastic stratigraphy simulations, and parametric Finite Element analyses to evaluate the geotechnical zone of influence as a metric to identify areas where the geological uncertainty significantly impacts geotechnical structures. In a synthetic case study, the methodology is demonstrated, highlighting that the propagation of geological uncertaintyto geotechnical analysis is non-uniform over the investigated domain. Additionally, the holistic framework enables the optimization of site investigations and allows for the assessment and improvement of geotechnical design robustness.

Keywords: Geological uncertainty, Geotechnical design, Finite Element analysis, Layer boundary uncertainty.

1. Introduction

Geotechnical projects typically include multiple subdomains to adequately describe both, natural subsoil conditions and geotechnical structures, such as embankments and foundations. Consequently, bonding subdomains have to satisfy certain relative behavior to each other, referred to as soil-structure interaction,where thesubsoil typically acts as the load-bearing domain but may also apply loading to the structure. Notably, subsoil conditions contribute significant uncertainty to geotechnical design due to sparse investigations and complex real-world data (Phoon et al. 2022). Subsoil uncertainty can basically be classified into two main sources, namely spatial variability and geological uncertainty. Spatial variability, or geotechnical uncertainty (GTU), can be understood as the location dependent variation of soil material properties of a specific soil type. Apaucity of knowledge about the spatial distribution of soil types, such as stratification, is regarded as geological uncertainty (GLU). Research on the impactof GTU on geotechnical structures began in the 1970s (Vanmarcke 1977) and has since yielded a robust foundation of tools and knowledge(Fenton and Griffiths 2008). In contrast, effects of GLU on geotechnical design were not considered for quite some time, likely due to computational limitations.Recent studies have expanded to the influence of GLU, covering core subdisciplines of geotechnics such asslope stability (Schöbi and Sudret 2017; Gong et al. 2019), spread foundations (Zhang et al. 2024), and tunnelling (Jiang et al. 2024). As shown in Zhang et al. (2024) GLU has substantial influence in reliability-based design of spread foundations for practically feasible site investigation densities.

In this paper an approach for a holistic analysis of GLU and geotechnical structures is presented. It demonstrates that integrating the knowledge of a geological conceptual model and stochastic stratigraphy simulation with parametric geotechnical Finite Element analyses (PFEA)allows for a combined assessment of GLU and the geotechnical zone of influence (GZI). Chapter 2 outlines the methodology for geological modelling and geotechnical analysis, while chapter 3 illustrates its application in a synthetic case study.

2. Workflow for stratigraphic boundary uncertainty and geotechnicalanalyses

Following the guideline of Baynes and Parry (2024) for developing an engineering geological model, the proposed workflow begins by constructing a conceptual model (CM) based on existing geological knowledge, available site investigations near the studied area and engineering judgement in the form of geological assumptions. In the next step, the CM is supplemented by observational data, e.g., boreholes. Based on this geological information, a stochastic stratigraphy simulation, as stated in 2.1, is conducted to assess the GLU. Subsequently, a Monte Carlo simulation is employed, whereby a PFEA is conducted for each geological realization. The GZI is determined from the ensemble of geotechnical analysis, as described in 2.2. A schematic representation of this workflow is illustrated in Fig. 1, providing a visual summary of the key steps and processes involved.

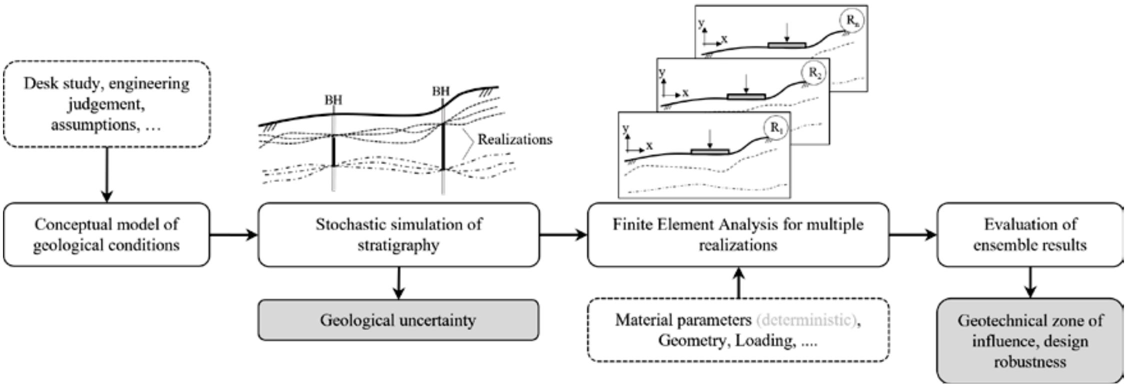

Fig. 1.Schematic workflow representation for stratigraphic boundary uncertainty and geotechnical analyses

2.1. *Geological uncertainty assessment*

Generally, stratigraphic geological models can be categorized into boundary-based and category-based models (Xiao et al. 2017). Boundary-based models, or stacked surface models, assume that stratigraphic boundaries within the area of interest are continuous. These models are relativelysimple but represent the most commonly used form of stratigraphic representation in geotechnical design.When the CM describes more complex geological conditions a category-based modelling approach needs to be adopted. The methodology presented in this paper is currently limited to boundary-based scenarios.

Reproduction of the assumed stratigraphic boundary variability is achieved throughConditional Simulations, a stochastic simulation method considered suitable for the geological boundary conditions under consideration. The assessment of geological uncertainty is performed entirely in Python, utilizing the geostatistical toolbox GSTools(Müller et al. 2022). GSToolsoffers a range of covariance models, kriging routines, and random field generators,providing the flexibility required. Detailed information onGSTools' functionality can be found in Müller et al. (2022). Stratigraphic boundary realizations are generated independently for each identified layer boundary in two dimensions, with the variogram model and kriging routine specified based on the CM, available investigation data, and engineering judgement. The latter is essentialdue to the (most of the time) limited number of site investigations, necessitating the incorporation of geological assumptions. Finally, the simulated surfaces are combined using stratigraphic rules to come up with three-dimensional realizations.

GLU, in terms of boundary variability, is quantifiedusing two approaches in the presented study. Since the ensemble mean of the Conditional Simulations aligns with the underlying kriging mean (Müller et al. 2022), the first measure of uncertainty is the kriging variance, specifically represented by the 95% confidence interval envelope of a stratigraphic boundary. However, this paper focuses on information entropy (H) as proposed byWellmann and Regenauer-Lieb (2012). Hquantifies geological model uncertainty and describes the degree of confidence in identifying the geological unit present at a specific location. In this study, the definition of H is slightly modifiedby normalizing itwith the logarithm of possible geological units, denoted by the normalized information entropyH_{norm}. Thus, $H_{norm} = 0$indicates complete certainty about the geological unit, whereas$H_{norm} = 1$signifies that all units are equally probable.

2.2. *Determination of geotechnical zone of influence*

In practical engineering, the GZI for a settlement calculation on homogeneous ground conditions is commonly defined as the depth where additional stresses from the loading do not exceed a certain percentage of the initial effective vertical stresses, for instance 20 %. However, this approach is not suitable for identifying the influence of GLU. Hence, a different approach is proposed. As stated earlier, for every geological realization a PFEA is performed using the Finite Element code Plaxis 2D (Bentley Systems 2024). Selected field results, such as stresses, strains, or deformations, are extracted from each simulation. Since different PFEA realizations feature non-unique mesh distributions, the results are interpolated onto a regular grid to facilitate statistical analysis. Depending on the problem and behavior investigated, different field variables form the basis for determining the GZI. For settlement analysis, the standard deviation of the volumetric strains has proven to be a valuable metric.

3. Synthetic case study

This chapter presents a synthetic case study to demonstrate the functionality and capabilities of the proposed framework. The boundary value problem involves a spread foundation for a 30 m wide and 60 m long warehouse. Subsoil conditions are assumed by three homogeneous layers, with the first boundary between an upper sandy-gravel layer and a clay dominated stratum. The second stratigraphic boundary separates the clay from the underlying bedrock. Warehouses are highly sensitive to differential settlements, therefore, an atypically dense investigation program with boreholes is assumed. Geological and geotechnical assumptions are provided in 3.1 and 3.2.A sketch of the synthetically generated ground truth for the upper and lower boundaries, the warehouse contours, highlighting the site investigation program and the calculation cross-section, is shown in Fig.2.Additionally, Fig. 2 includes elevation contours of the boundaries, with a color bar on the right-hand indicating elevation values.

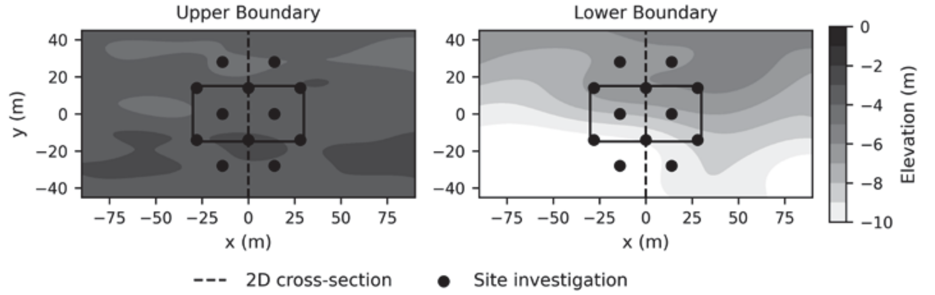

Fig. 2.Synthetic ground truth for upper and lower boundary, warehouse contour and site investigation program

3.1.*Geological assumptions*

The CM is based on the geological history of a valley initially filled with clay, which was later partially eroded and overlaid by a sandy-gravel layer. Site investigations indicate a mean depth of -3.5 m for the upper and approximately-8.0 m for the lower boundary, with the latter exhibiting almost a linear trend parallel to the y-axis. Correlation lengthsalong the y-axis are defined as 10 m for the upper and 14 m for the lower boundary.In the x-direction, the correlation lengths are assumed to be twice as large to account for the underlying anisotropy.Input parameters for the stochastic simulation are derived from the CM, site investigations and engineering judgement. Ordinary kriging is applied to simulate the upper, while universal kriging is used for the lower boundary to account for its linear trend.

3.2. *Geotechnical assumptions*

From a geotechnical perspective, the Hardening Soil Small (HSS) model (Benz et al. 2009) is considered a suitableconstitutive model to represent the soil behavior of the clay and sandy-gravel layers, as it follows a double hardening approachthat accounts for stress dependent stiffness and shear stiffness degradation. The material parameters used are listed in Table 1, further details on the HSS model can be found in Benz et al. (2009). The concrete slab with a thickness of 0.5 m, modeledusing a volume approach, and the bedrock are represented with a linear elastic material model. A Young's modulus of $32{\cdot}10^6$ MPa is used for the concrete and $1{\cdot}10^6$MPa for the bedrock. The model domain was assumed with a depth of 14 m and a length of 180 m, discretized by a mesh with approximately 11,500 elements with a fourth order shape function. As a representative loading scenario, a constant surface load of 60 kPa is applied on top of the concrete slab. No groundwater table is considered in this study and the interface strength is adopted from the sandy-gravel layer.

Table 1. Hardening Soil material parameters for the clay and sandy-gravel soil layers.

Parameter	Clay	Sandy-gravel	Unit
γ_{unsat}	19.0	21.0	kN/m^3
$E_{50}^{ref}, E_{oed}^{ref}$	10,000	50,000	kPa
E_{ur}^{ref}	35,000	105,000	kPa
m	0.8	0.6	–
c'	5.0	0.0	kPa
φ	28	32	°
$\gamma_{0.7}$	0.0002	0.0001	–
G_0^{ref}	82,000	182,000	kPa
p^{ref}	100	100	kPa

3.3. *Combining geological uncertainty and geotechnical zone of influence*

The goal of the proposed workflow is to investigate the influence of GLU on geotechnical structures, using the GZI to identify areas where GLU has significant geotechnical implications. The process for the determination of GLU is described in 2.1 and the evaluation procedure of the GZI can be found in 2.2. Fig. 3 illustrates the results: the left side shows GLU in terms ofH_{norm} , while the right side displaysthe associated variability in the numerical analysisrepresenting the GZI by the standard deviation of the volumetric strains ($SD\varepsilon_{vol}$). $SD\varepsilon_{vol}$ is evaluated from the ensemble of all PFEA interpolated on a regular grid. The contour plot of H_{norm} highlights stratigraphic boundary variability, with the greatest GLUobserved on the right side, where the upper and lower boundaries are expected to intersect. However, as revealed by the right plot, the area with the highest GLU, indicated by a higher $SD\varepsilon_{vol}$, lies outside the GZI and therefore does not influence the slab's settlement behavior. Thus, reducing GLU in this area has a negligible influence on the geotechnical analysis. In contrast, the area in the vicinity of the slab (as expected), especially at the upper layer boundary, is critical for increasing the robustness of the settlement prediction.

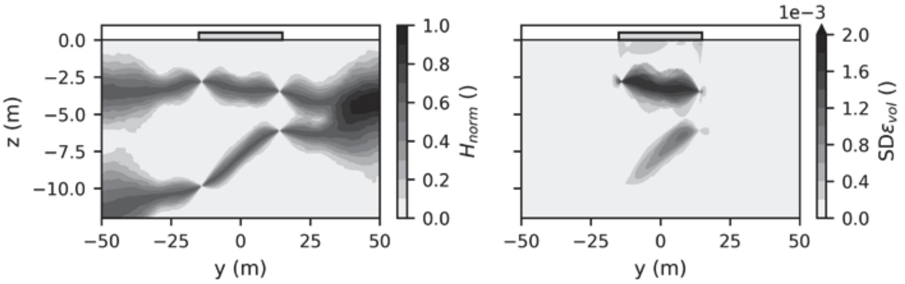

Fig. 3.GLU in terms of H_{norm} (left) and the GZI with related strain field variability represented by$SD\varepsilon_{vol}$ (right)

4. Conclusion

In the scope of this paper a holistic framework for assessing the influence of geological uncertainty (GLU) on geotechnical structures by integrating a conceptual geological model, stochastic stratigraphy simulations and parametric finite element analyses is presented. The geotechnical zone of influence (GZI) is introduced as a probable metric to identify areas where the GLU significantly affects geotechnical design. Results demonstrate that the propagation of GLU to the geotechnical analysis is not uniform across the entire domain, highlighting the need for a holistic evaluation of GLU and GZI. This combined analysis of GLU and GZI enhances understanding of uncertainty propagation in geotechnical design. Additionally, this holistic approach provides a basis for optimizing secondary investigation strategies, yielding an increased design robustness. Extension of the proposed framework to more complex geological conditions, geotechnical problems and the identification of further metrics to evaluate the GZI are subject of current research and will be reported in the future. Furthermore, its applicability to real case studies remains to be investigated.

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