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CONDITIONAL RANDOM FIELDS FOR SIMULATING SPATIAL VARIABILITY OF GEOTECHNICAL PARAMETERS IN TUNNELLING

Summary: *In times of fast urbanization, underground infrastructure has taken primacy for servicing the city development. Shield tunnel construction is facing significant challenges due to geological uncertainty and limited availability of site-specific test data. As proven by recent works, tunnel design can be done more precisely within the probabilistic frameworks by considering the soil spatial variability, rather than using conventional deterministic-based approaches. In spatial variability modelling, the problem of incomplete utilization of known borehole soil parameters within the unconditional random fields can be overcome by generating conditional random fields. This paper presents a comprehensive review of the CRF application for spatial variability assessments in tunneling in the last five years. It finds that, when applying CRF-based probabilistic approaches, parameter uncertainty is undeniably reduced, and tunnel performance assessments are improved. Since CRFs have rarely been used for tunnel performance assesment, the paper recognizes research gaps that are of great interest to be further investigated in the future.*
Keywords: *conditional random fields, CRF, spatial variability, tunnelling, probabilistic analysis*

PRIMENA USLOVNIH SLUČAJNIH POLJA ZA SIMULACIJU PROSTORNE VARIJABILNOSTI GEOTEHNIČKIH PARAMETARA U TUNELOGRADNJI

Rezime: *U vremenu ubrzane urbanizacije, podzemni infrastrukturni objekti preuzeli su primat u procesu razvoja gradova. Izgradnja tunela metodom štita praćena je velikim izazovima u pogledu geoloških nepouzdanosti i nedostupnih merenih podataka na istražnom području. Prema novijim istraživanjima, proces projektovanja tunela može biti poboljšan uzimanjem u obzir prostorne varijabilnosti tla kroz probabilističke analize, za razliku od konvencionalnih determinističkih pristupa. U procesu modeliranja prostorne varijabilnosti, problem nepotpune integracije poznatih parametara tla iz bušotina rešava se generisanjem uslovnih slučajnih polja (CRF). Cilj ovog preglednog rada jeste sagledavanje primene CRF teorije za procenu prostorne varijabilnosti parametara tla za potrebe tunelogradnje u poslednjih 5 godina. Zaključeno je da postoji neosporna redukcija nepouzdanosti u projektovanju i napredak u pogledu inženjerskih analiza tunela pri primeni CRF-probabilističkog pristupa. CRF metoda se do sada retko primenjivala u numeričkim inženjerskim analizama tunela, pa s tim u vezi ovaj rad sadrži i preporuke za dalja istraživanja.*
Ključne reč: *CRF, prostorna varijabilnost, tunelogradnja, probabilistička analiza*

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1. INTRODUCTION

In the last few decades, the underground transportation system has been developing all over the world at a very fast pace, due to high social and economic demands and environmental limitations. Comparing the underground structures to the above-ground ones leads to a certainty – the former ones are located in spatially variated soil or rock, which makes them very complex in terms of design, construction and maintenance. One of the dominant role-players in the system, shield tunnels, have faced significant challenges when it comes to considering the real and uncertain geological conditions.

Due to complex tectonic and depositional processes, the soil and rock physical and mechanical properties can considerably vary from one point to another in 3D space. Spatial variability, if not taken into account during the structural performance analyses, can be the cause of incomplete and inaccurate assessments and unsafe design.

Majority of the research work and design approaches in the field of geotechnical engineering have been based on deterministic analyses, in which soil and rock parameters are treated as constant. Owing to the omittance of parameter variability and uncertainty, and consequently generating non-conservative estimates, these analyses are gradually being replaced by the probabilistic methods [10], [7], [12], [20], [19], [18]. Probabilistic analysis methods based on spatial variability have been applied to investigate the probability of failure, working performance, and failure mechanisms of tunnels with the aid of numerical simulation software, such as FLAC 3D or ABAQUS [21].

As for the existing probabilistic analysis methods, the uncertainties of soil properties can be simulated using random variables with certain spatial correlations [22], [1], [11], [14]. However, the random field theory (RFT)-based site characterization has taken the primacy. In the RFT, random fields (RFs) are generated using the soil properties obtained from the boreholes, after which the soil parameters at the site are randomly produced within the calibrated random field and can be used for following analyses. Even though the random field theory represents both an effective and efficient set of tools for the stochastic geological heterogeneity characterization, a traditional unconditional random field (UCRF) approach doesn't fully utilize the soil properties generated from the borehole locations, which may lead to overestimating the site variability [11]. This is an issue that can be overcome by generating conditional random fields (CRFs) which incorporate the soil properties at borehole locations, thus reducing the parameters uncertainty. However, this is a practice-demanding task to complete, considering the operational complexities and multidisciplinary dependence of construction operations [18].

There have been efforts put into summarizing the spatial variability simulations in underground construction, such as [21], but with the application of unconditional random field methods mostly. In those terms, this paper aims at reviewing the possibilities of constraining the UCRFs to reflect the "certain" borehole data by generating the CRFs, in order to take into account the soil spatial variability for tunneling procedures. The following chapters will shortly present the UCRF and CRF differences of the utmost importance, and the existing applications of CRFs for different tunnel-performance assessments, for the time frame defined by searching the Web of Science and Scopus databases.

2. RANDOM FIELD THEORY IN TUNNELLING

In the era of extreme urbanization, it is not unusual for tunneling and deep excavation procedures to take place in adjacent locations simultaneously. Consequently, complex mechanisms must be expected both in soil and rock, and in adjacent infrastructure. For such building environments, design, evaluation, and prediction of the underground construction performances has become an essential issue [21].

The process of assessing tunnel performances requires a complete and comprehensive characterization of the input soil parameters, along the tunnel longitudinal or horizontal direction. Considering the fact that these parameters could only be measured and known at borehole locations, as well as that the site investigations' scope is often budget-restricted, some kind of parameter interpolation has to be involved. Even though different spatial interpolation methods have been widely adopted in the current practice, they are of limited capabilities when it comes to spatial variability of soil properties. This is where the random field theory-based site characterization has been taking its spot ever since the 2000s.

In the RFT-based site characterization, the statistical information associated with random fields (e.g., the mean value, standard deviation, and spatial correlation structure) is calibrated using the soil properties provided by the borehole in-situ measurements. The soil properties at the site are then randomly generated using the calibrated random field, and after that are implementation-ready for the performance analyses.

Regarding the RFT application in tunneling, extensive research has been conducted by many authors. For example [15], [6], [4], [5] investigated the tunnel face stability using UCRFs, [7] and [16] used CRFs for the assessment of tunnel longitudinal performance, [17], [8] and [9] investigated tunneling-induced ground deformations by employing the random-field based probabilistic analyses. Research conducted in the domain of conditional random field (CRF) application in tunneling will be discussed in the next chapters of this paper.

2.1. Unconditional and conditional random fields

In general, a certain degree of soil properties correlation in both the horizontal and vertical directions can be observed at a project site. The spatial correlation decreases with an increase in relative spatial distance, which can be characterized by the scale of fluctuation [2].

Although the inherent spatial variability of the soil properties could be expressed through UCRF generation process, the determined properties obtained from borehole locations cannot be incorporated. This limitation can have a significant impact on predicting the tunnel performances, and furthermore can lead to greater accumulated uncertainty (Fig. 1). In order to address this growing issue, the conditional random field approach was developed to constrain the traditional random fields using the obtained borehole data [3], [13].

In spite of the fact that real-life geotechnical problems are three-dimensional, most of the existing studies adopted a two-dimensional RF approach in modelling the soil spatial variability. This is due to the computing challenges in generating a full-scale high-resolution 3D conditional random field. Even the simulation of a full-scale 3D unconditional random field is a high-demanding task that requires significant computational costs.

Also, in terms of integrating CRFs into probabilistic analysis frameworks, it can be difficult to overcome the operational complexities and multidisciplinary dependence of construction operations. A potential solution to the above-described problems lies in automatic generation of the CRF-based probabilistic analysis model from a parametric model [18].

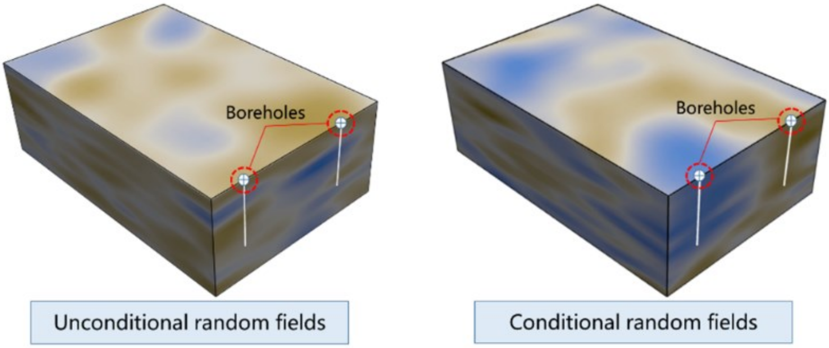
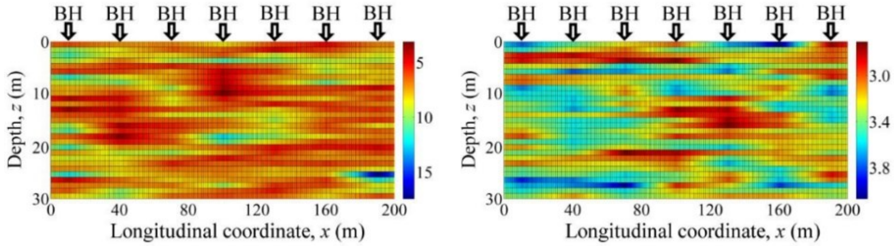


Figure 1. Comparison between unconditional and conditional random fields (after [18])

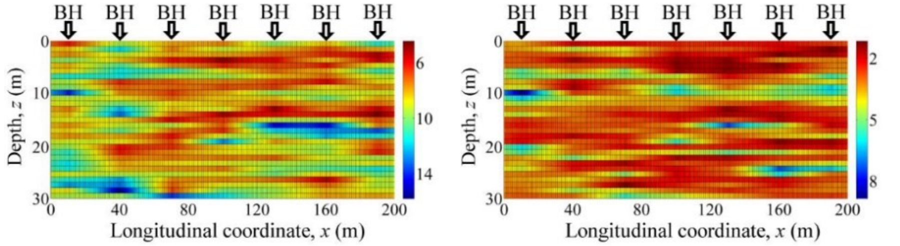
3. APPLICATION OF CRFS IN TUNNELLING

The scope of this paper covers the time period of 2018 – 2023, which has been generated as such through the Web of Science and Scopus search engines. This encourages the fact that conditional random fields are still rarely used for simulating the spatial variability in underground construction, even though they are capable of making a true difference in structural performance predictions, as presented in the following works.

A new framework for the probabilistic analysis of the tunnel longitudinal performance was presented by [7] and consisted of a few steps. First, the characterization of the project site was conducted by randomizing the soil properties with Hoffman-sampled conditional random field assuming the lognormal distribution (Fig. 2). Then, the deterministic analysis of the tunnel longitudinal performance (settlement, longitudinal rotation, longitudinal bending moment, and longitudinal shear force) was managed by using the one-dimensional finite element method (FEM) and 2D analytical solution. Finally, a number of Monte Carlo simulations (MCS) were performed to determine the probability of failure for each tunnel cross section. Authors concluded that the inherent spatial variability of the soil properties cannot be fully characterized with the traditional linear interpolation methods, nor the unconditional random fields, but only with conditional random fields, which are the best solution to reduce the soil properties uncertainty and predict the tunnel longitudinal performance. They also stated that the increase in the borehole density could result in more accurate evaluation of the longitudinal performances.



(a) Effective cohesion (c, kPa) (b) Effective friction (ϕ, ×10 °)



(c) Horizontal ground stiffness (k_h, $\times 10^3$ kN/m^3) (d) Vertical ground stiffness (k_v, $\times 10^4$ kN/m^3)

Figure 2. CRF simulated soil properties (after [7])

An efficient method for a shield-driven tunnel reliability analysis using spatial random fields is proposed in [9], by combining a response surface method (RSM) and spatial random field method. Spatial random fields (Fig. 3) were derived as Gaussian stationary using local regression and conditionally discretized by combining the Method of Anchored Distribution and software FLAC3D with their newly designed general driver. The method was applied to calculate the probability of failure of the 5th and 6th metro lines in Tianjin, China. The results indicated that a Gaussian stationary field could be established for multiple soil layers using local regression and spatial conditional discretization of multivariate, and that a subset Monte Carlo (SMC) algorithm could efficiently calculate the probability of failure (or reliability index).

A novel method for simulating a 3D conditional random field on incomplete site data has been proposed by [19]. In two effective steps, conditional random fields can be generated for a full-scale 3D domain without engaging in mathematical operations of large matrices, by using two novel techniques – sounding-wise Gibbs sampler (GS) and depth-wise Monte Carlo simulation (MCS). First step consists of simulating the missing data by augmenting it to achieve the dense-lattice structure (meaning that all the boreholes are of the same depth and vertical sampling interval is smaller than the vertical SOF). This process makes the data ready for the step 2 – simulating 3D CRF. The method was applied to a virtual 3D underground domain, for which the spatial variability of the undrained shear strength was modelled (Fig. 4). It was concluded that conditioning on the site data can have a significant effect on the reliability of a geotechnical structure if the boreholes are close to it. Even though the method hasn't been tested on a tunneling case study yet, a great potential for such purposes has been recognized, which makes it suitable to include in this paper.

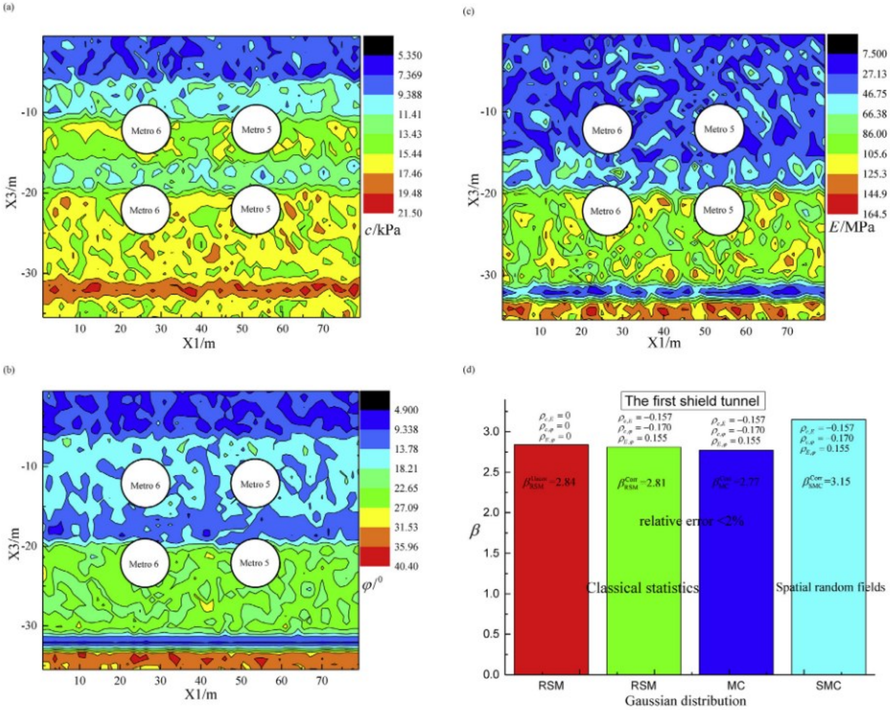


Figure 3. Spatially conditioned realizations of: (a) cohesion, (b) internal friction angle, (c) Young's modulus and (d) probability of failure of the maximal ground surface settlement according to different simulation methods (after [9])

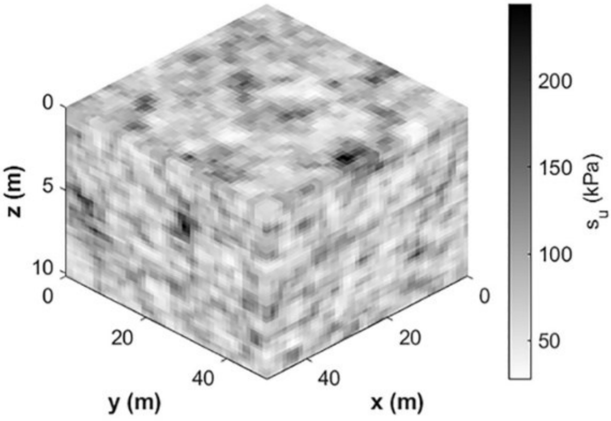


Figure 4. A 3D conditional random field realization of undrained shear strength s_u (after [19])

A probabilistic horizontal convergence reconstruction method based on the CRF simulation of the tunnel structural performance is proposed by [16]. They generated 1D stationary and ergodic conditional random field by incorporating a historical record of convergence sensor monitoring results along the tunnel longitudinal direction (Fig. 5). Monte Carlo simulation was adopted to generate possible realizations and the mean of realizations was considered as the maximum likelihood reconstruction. Through a case study of Shanghai Metro Line 2 shield tunnel, the proposed convergence reconstruction method was verified, and its effectiveness in reconstructing time-variant data was confirmed. Also, it was shown that, by applying this method, the optimization of the sensor deployment scheme could be obtained even before the monitoring process.

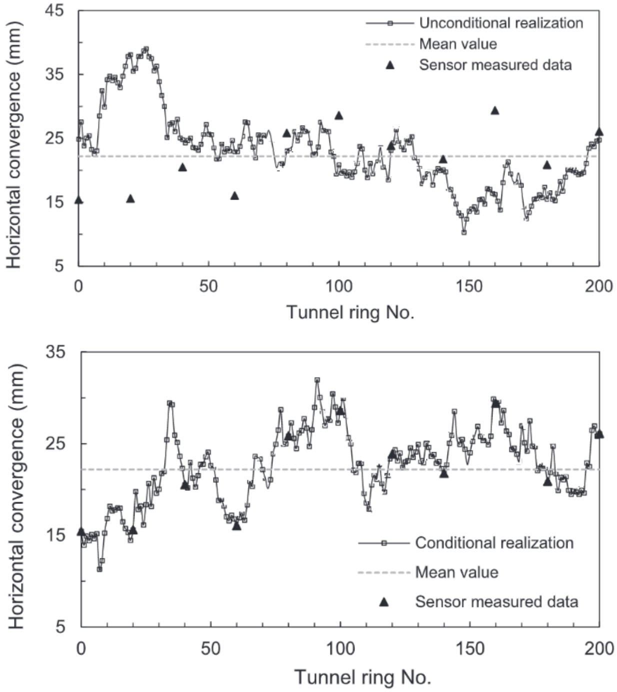
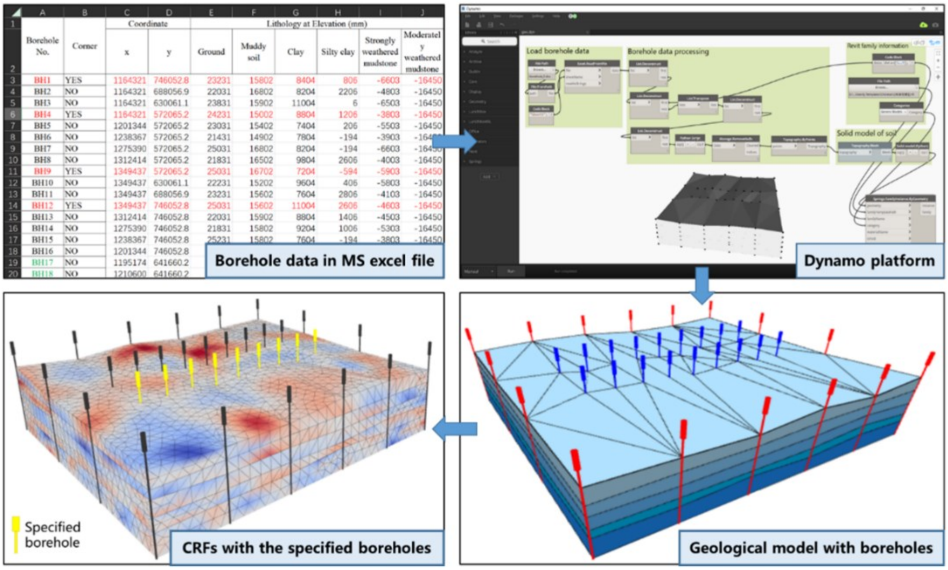


Figure 5. Unconditional (upper) and conditional (lower) realization using the sensor measured data (after [16])

PM-CRF engine for object-oriented parametric geological modelling using the conditional random fields was introduced in [18]. This concept is suitable for achieving CRF characterization based on the availability of borehole data, the initial evaluation of soil properties, and the property differences between soil layers. Parametric geological model can be automatically generated through processing the borehole data with Excel and Dynamo, creating the solid soil model and configuring the corresponding parametric components with the soil properties (Fig. 6). They also developed a unique PM-CRF-PSA interoperability framework, in which PSA model for shield tunnel-safety assessment is generated automatically with a WebGL-based platform. It can be utilized for generating both 2D and 3D PSA models for assessing the ground surface settlement and convergence deformation of the tunnel structure. This PM-CRF-PSA approach was applied to a case study, and it was concluded that if the uncertainties of soil properties are considered, PSA spans more potential failures than does the traditional DSA.



Borehole No.	Corner	Coordinate		Lithology at Elevation (mm)					
		x	y	Ground	Muddy soil	Clay	Silty clay	Strongly weathered mudstone	Moderately weathered mudstone
BH1	YES	1164321	746052.8	23231	15802	8404	806	-6603	-16450
BH2	NO	1164321	688056.9	22031	16802	8204	2206	-4803	-16450
BH3	NO	1164321	630061.1	23831	15902	11004	6	-6503	-16450
BH4	YES	1164321	572065.2	24231	15002	8804	1206	-3803	-16450
BH5	NO	1201344	572065.2	23031	15402	7404	206	-5503	-16450
BH6	NO	1238367	572065.2	21431	14902	7804	-194	-3903	
BH7	NO	1275390	572065.2	25031	16802	8204	-194	-6603	
BH8	NO	1312414	572065.2	21831	16502	9804	2606	-4003	-16450
BH9	YES	1349437	572065.2	25031	16702	7204	-594	-5903	-16450
BH10	NO	1349437	630061.1	22231	15202	9604	406	-5803	-16450
BH11	NO	1349437	688056.9	23231	15602	7604	2806	-4103	-16450
BH12	YES	1349437	746052.8	25031	15602	11004	2606	-4603	-16450
BH13	NO	1312414	746052.8	22031	15902	8804	1406	-4503	-16450
BH14	NO	1275390	746052.8	21831	15802	9204	1006	-5303	-16450
BH15	NO	1238367	746052.8	25231	15802	7604	-194	-3803	-16450
BH16	NO	1201344	746052.8						
BH17	NO	1195174	641660.2						
BH18	NO	1210600	641660.2						

Figure 6. Generation process of soil layer-based CRFs (after [18])

4. CONCLUSIONS

The main objective of this paper was to present a short review of the developments in tunneling engineering in regard to spatial variability assessment with conditional random field theory. Since most of the existing work in the tunnel-performance probabilistic analyses has been done by unconditional random field-site characterization methods, there hasn't been a lot of material to bring to the review. However, this can only mean that CRF-in-underground-construction is a research prone engineering domain and that the future holds new solutions to this growing issue.

Spatial variability, as a widespread and real phenomenon in nature, has to be considered when assessing and predicting tunnel performance from different perspectives, such as tunnel face stability, longitudinal performance, and tunneling-induced ground deformations. Much research has been conducted regarding this topic, and it has been concluded that only the probabilistic approaches could fully capture complex soil and rock geological nature. Most of the probabilistic tunnel performance analyses have relied on the traditional random field-site characterization. However, the best way to produce accurate and comprehensive performance predictions is to condition the random fields with the data obtained from the site investigations.

So far, conditional random fields have been used to support the probabilistic analysis of tunnel longitudinal performance, in reliability analysis of shield-driven tunnels, for modelling the incomplete site data with augmentation processes, for probabilistic time-invariant horizontal convergence reconstruction and for automatic generation of CRF-based probabilistic analysis model from a parametric model. Even though all of these applications represent significant and innovative work, there are many remaining scientific problems to be explored.

First of all, since the site-characterization process can only be realistically observed as a three-dimensional problem, more attention should be drawn to formulating full-scale 3D CRF simulation methods which could overcome the computational and operational complexities. Also, low efficiency of the manual modelling should be addressed in the light of the fast and well-developing digital technologies. One potential solution for these issues has already been suggested by [18] and discussed in the chapter above. Finally, since the majority of the research works assume underground structures to be embedded in homogenous geological formations, one of the key research directions, that's applicable to any geotechnical problem, is dealing with complex geological conditions.

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