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Modeling the swelling extent of argillaceous soft rock using the PLAXIS swelling rock model

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Abstract

This paper addresses the challenges of numerically calculating the effective swelling extent in a test gallery situated in an argillaceous soft rock lithology using PLAXIS 2D and employing two different approaches, namely applying volumetric strain and the "PLAXIS Swelling Rock Model". The focus is on a localized section of a tunnel excavation where swelling occurs in the invert due to artificial irrigation in an otherwise dry but swellable rock mass. Accurate long-term modeling of the swelling behavior of such lithologies is crucial for understanding the acting stresses on underground structures and improving the overall rock mass characterization. However, maintaining in-situ test equipment for extended periods on active tunnel construction sites for validation reasons often proves challenging.

The study utilizes long-term in-situ monitoring data from extensometers, stress strain meters, geodetic targets and a chain inclinometer installed in a test gallery of the Angath adit tunnel in Tyrol, Austria, combined with laboratory swelling test results. These datasets and associated back calculations are utilized as the basis of this study. Two different approaches for a prognosis of the final swelling extent in the invert of the test gallery on the basis of laboratory test results are used and compared with one another.

Results show that while numerous adjustable parameters in the modeling process of the PLAXIS Swelling Rock Model allow for flexibility, laboratory test results are not sufficient as sole input data to account for the model complexity and potential inaccuracies in achieving a realistic prediction. The problem of upscaling from rock to rock mass parameters appear to have a substantial influence on the results.

Keywords

Argillaceous soft rock, hard soil/soft rock, swelling rock model, numerical modeling

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1 Introduction

The complex behavior of argillaceous soft rocks poses significant challenges in geotechnical engineering. The Unterangerberg formation, a lithology representative of the Hard Soil/Soft Rock (HSSR) spectrum (Marcher et al. 2020), exemplifies such materials due to its high variability, and propensity for swelling when in contact with water. Swelling phenomena influenced by mineralogical composition and environmental conditions can induce stresses and displacements in underground structures, thereby complicating their design and long-term performance predictions (Kirschke 2010; Schädlich et al. 2013).

Previous research on the lithology by means of an in-situ testing campaign within a designated test gallery (see 2.2) by (Metzler et al. 2024) provided long-term insights into the swelling behavior of the Unterangerberg formation under in-situ conditions. The systematic monitoring campaign included extensometers, stress strain meters, geodetic targets, and a chain inclinometer and revealed the influence of the scale effect between laboratory and in-situ test results as well as of time-dependent swelling phenomena in the rock mass. The in-situ monitoring program on the active tunnel construction site allows for the observation of long-term effects of swelling-induced displacements and stresses. The aim of this paper is to compare the different assumptions and parameters in different swelling approaches to identify the most realistic method to accurately understand and model these observed phenomena with the aim of improving long-term predictive capabilities of the rock mass behavior.

2 Background

The swelling behavior of argillaceous soft rock, such as the Unterangerberg formation, arises from complex interactions between mineralogy, moisture content, and stress conditions (Rauh 2009; Kirschke 2010; Cudmani et al. 2021). Laboratory tests have consistently shown higher swelling potentials than in-situ conditions, a discrepancy attributed to scale effects, boundary constraints, and varying degrees of saturation (Kirschke 1996; Rauh 2009). To minimize these differences, numerical models can be employed to simulate the in-situ field behavior of these materials (e.g., Anagnostou 1993; Schädlich et al. 2013).

This study leverages data from a monitored test gallery to perform a general prognosis using PLAXIS 2D with a particular focus on employing the *PLAXIS Swelling Rock Model* by (Schädlich et al. 2013) and comparing it to swelling phenomena modeled using volumetric strain. The Swelling Rock Model incorporates a large variety of material-specific parameters, such as elastic and plastic swelling properties. However, the large number of variables and the challenge of upscaling from rock to rock mass parameters complicate the realistic modeling of the situation. By combining in-situ field data, laboratory results, and numerical modeling, this research aims to address these challenges and propose potential pathways for improved long-term predictive modeling.

2.1 Lithology

The investigated lithology is called the Unterangerberg formation, a representative example of argillaceous soft rock within the HSSR spectrum. It consists of prodelta sediments, predominantly of millimeter-scale alternating layers of claystone, marlstone, and sandstone, with significant mineralogical heterogeneity. The interbedded nature of the lithology results in considerable variability in its mechanical properties. A key feature beside its sedimentary layering is its swelling potential linked to the presence of clay minerals, particularly smectite. (Ortner 2003; Sommer et al. 2017; Erharter et al. 2019)

The swelling behavior of the lithology was assessed by means of laboratory tests, including free swelling, swelling pressure, powder swelling, and Huder-Amberg swelling tests. These tests indicate that the maximum swelling potential depends on both the clay mineral content and the degree of saturation. Free swelling tests yielded potential uplift values ranging from 4.4 to 6.4 % for the investigated rock mass, while the Huder-Amberg swelling potential reaches a maximum at 2.1% axial strain at 25 kPa as depicted in Fig. 1. Despite these results, the in-situ swelling potential is influenced by geological discontinuities, heterogeneity, and limited water availability. Also, due to the scale effect, laboratory tests yield more conservative swelling parameters than observed in the in-situ field test (Rauh 2009). This common discrepancy accentuates the importance of correlating laboratory and in-situ field data to achieve realistic characterizations of swelling behavior.

Fig. 2 shows the Huder-Amberg swelling test compression curve of a laboratory test conducted on the finely interlayered material. According to (Paul 2023) the reloading and final unloading curves are extrapolated to determine the intersection point whose associated stress lies at approximately 3000 kPa, which characterizes the pressure above which swelling is no longer possible.

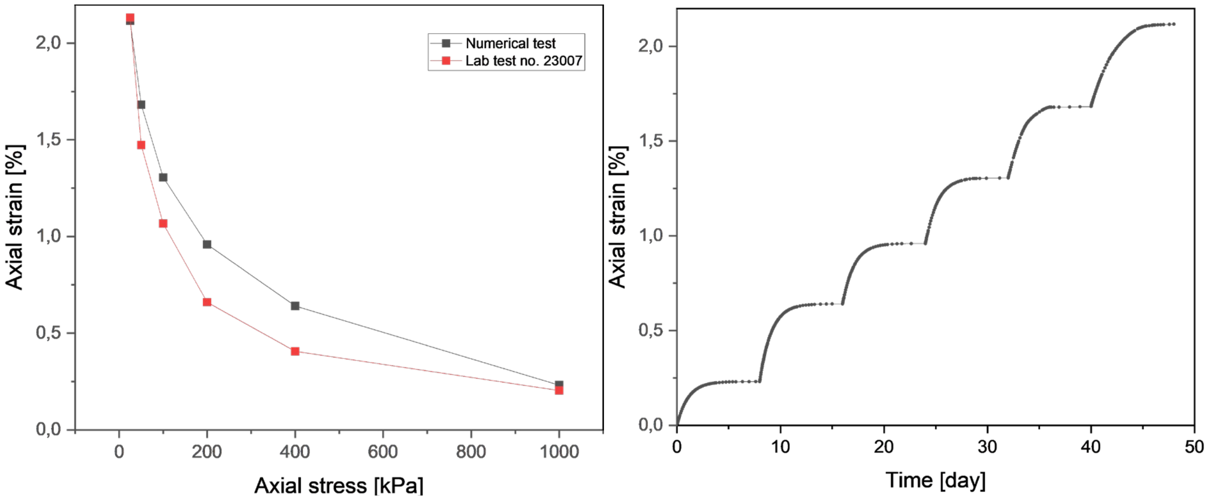

Fig. 1 Left: Swelling potential of Huder-Amberg test result number 23007 (red) and back-calculated, axisymmetrically modeled Huder-Amberg test for model calibration using PLAXIS 2D (gray). Right: Test result of the back-calculated Huder-Amberg test for calibrating the PLAXIS Swelling Rock Model.

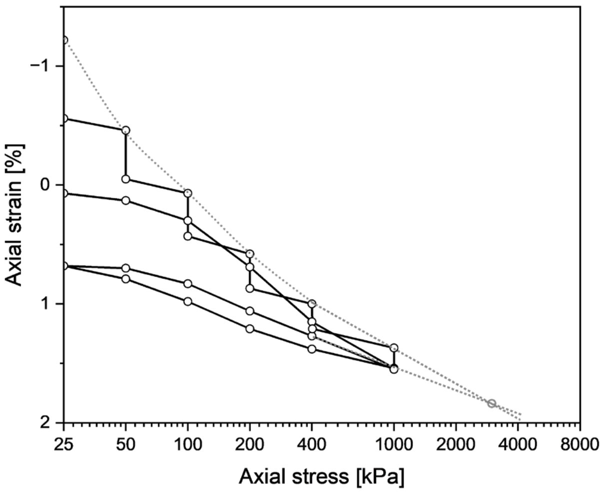

Fig. 2 Huder-Amberg swelling test compression curve for test no. 23007. Extrapolation of reloading and final unloading curves determines the pressure above which swelling is no longer possible at approximately 3000 kPa .

2.2 Tunnel project

The studied test gallery is part of the Angath adit tunnel located in Tyrol, Austria. The construction project is part of the “Schaftenau – Radfeld” section of the trans-European railway connection Berlin – Palermo and the northern access route to the Brenner Base Tunnel through the Unterangerberg formation. The Austrian Federal Railways are constructing the Angath adit tunnel from 2023 to 2025 as an exploratory tunnel for the subsequently excavated adjacent main tunnel. During the operational phase it will serve as the emergency tunnel to the side of the double-track main railway tunnel, connected by six cross-passages. One of the cross-passages serves as an in-situ test gallery during the construction phase and is equipped with numerous geotechnical monitoring devices, multifold extensometers among them (e.g., 5-fold extensometer in the tunnel invert as seen in Fig. 3) serving as calculation basis in this study. Moreover, an irrigation field is installed in the invert in the form of 3.80 m long boreholes in a one-by-one meter raster, and irrigated biweekly. In this study, a two-dimensional monitoring cross-section within this irrigation field in the test gallery is modeled, and its input parameters are taken from laboratory swelling test results conducted on drill core samples from the rock mass surrounding the test gallery. The drill cores have a diameter of approximately 20 centimeters and are overdrilled in the laboratory shortly before testing to retain in-situ field conditions to a greater extent.

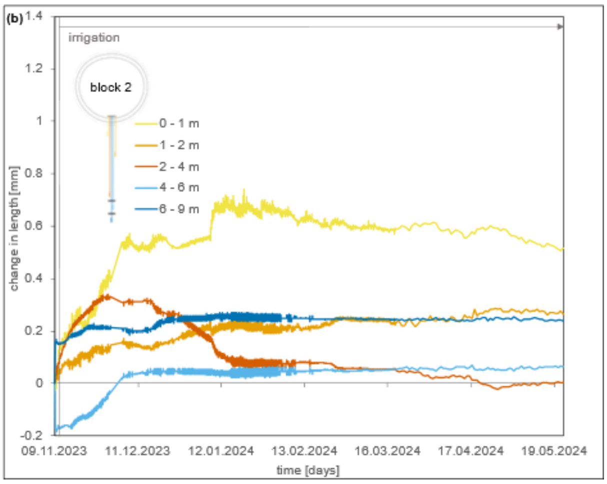

Fig. 3 Change in length of invert extensometer from tunnel perimeter into the rock mass in the ranges 0 – 1 m, 1 – 2 m, 2 – 4 m, 4 – 6 m, 6 – 9 m distance. Positive displacement values are elongations while the negatives are shortenings. Figure taken from (Metzler et al. 2024).

3 Methodology

The study applies two different simplified approaches to model the swelling phenomenon in the argillaceous lithology using PLAXIS 2D (Bentley Systems 2023) to assess the effective swelling extent. The swelling model implementations are detailed as follows.

The first method models swelling by applying volumetric strain in a defined section of the rock mass underneath the invert of the cross-section. Following the engineering approach of (John et al. 2009) and using the hypothetical modulus of elasticity by (Pöttler 1990), the swelling pressure is assumed to lie in the range of 300-400 kPa. (John et al. 2009) argues that basing the determination of meaningful swelling pressure on laboratory test results is dependent on the factors of scale effect, stiffness ratio of surrounding ground and tunnel lining as well as the in-situ stress and water conditions, which accumulates in difficult predictions for swelling load conditions. The Huder-Amberg test result yields a maximum swelling strain of 2.1%. In accordance with (Kirschke 2010), the swelling pressure acting on the lining does not exceed 400 kPa in observed conditions. When calibrating the 2D model of the cross-section to fulfil this condition, a maximum swelling strain of 0.21% directly below the invert is reached. This value accounts for approximately 10% of the laboratory test result, which is in accordance with (John et al. 2009). As shown by the geometry in Fig. 4 and Fig. 5, this amount is assumed to reduce outwards to 75%, 50%, and 25%, respectively.

The second approach models swelling strain by considering Huder-Amberg swelling test results and implementing the PLAXIS Swelling Rock model. The maximum swelling pressure employed in PLAXIS 2D was assumed on the basis of the maximum axial stress by multiplying the sum of the 60 meters overburden plus 8 meters tunnel diameter with the unit weight of 25 kN/m³. This results in the estimated swelling pressure of approximately 1700 kPa. By extrapolating the reloading and unloading curves of a Huder-Amberg swelling test, as depicted in Fig. 2 in accordance with (Paul 2023), the estimated maximum axial stress lies at approximately 3000 kPa, which is generally within the same order of magnitude. The axisymmetric numerical model of the earlier mentioned laboratory test involves maintaining the axial stress of each loading step until close to zero increase in strain is measured (as depicted in Fig. 1). The resulting calibrated model parameters are then used to predict the final in-situ swelling displacements in the modeled cross-section.

Although the modeled lithology shows a small-scale alternating bedding in the millimeter range, the laboratory test modeled in this study as well as the in-situ scale cross-section were assumed as smeared homogeneous material for means of simplicity. In both approaches, the construction phases as well as material parameters – except the ones regarding swelling processes – are set and kept equal for reasons of comparability. In the initial stage, the rock body of dimensions 200 by 116 meters is defined, an earth pressure coefficient K_0 of 0.5 is assumed and the material based on laboratory test results (see Table 1 for values) is assigned. The second stage accounts for pre-relaxation, which is set to 50%. In the third stage, the full-face excavation of the cross-section takes effect. Stages 4 and 5 account for the installation of C25/30 shotcrete with a thickness of 0.20 meters with early and late material parameters, respectively (“young” shotcrete with E = 3 GPa vs. “old” shotcrete with E = 15 GPa). Swelling only occurs in the sixth and last stage. Thus, this is the only altered stage for the three different swelling methods employed. The displacements in PLAXIS 2D are reset to zero after the excavation and before the start of the irrigation phases. This step ensures the exclusion of the excavated-induced displacements or stress measurements not attributed to the swelling behavior.

Table 1 Ground properties for Unterangerberg formation based on back calculations of laboratory test results coupled with in-situ monitoring data in sections where no swelling occurs

Parameter	**Value**	**Unit**
Modulus of elasticity	10	GPa
Cohesion	15	MPa
Friction angle	25	°
Poisson’s ratio	0.20	-
Unit weight	25	kN/m³

4 Results and discussion

The heave of the tunnel invert due to swelling results in a magnitude of 2.2 mm using the volumetric strain approach as depicted in Fig. 4. The PLAXIS Swelling Rock Model leads to a higher value of 5.7 mm (Fig. 5). Both approaches overestimate the swelling potential, although when comparing the numerically calculated displacements to those of the in-situ measurements of 1.3 mm, both approaches yield results in the appropriate range.

Both approaches are simplified methods for predicting argillaceous swelling. Both show swelling-induced invert heaves in the depths of the first one to two meters below the invert, which is consistent with the measurement results of the installed invert extensometers (see Fig. 3). Beyond this, the effects on the rock mass are minor.

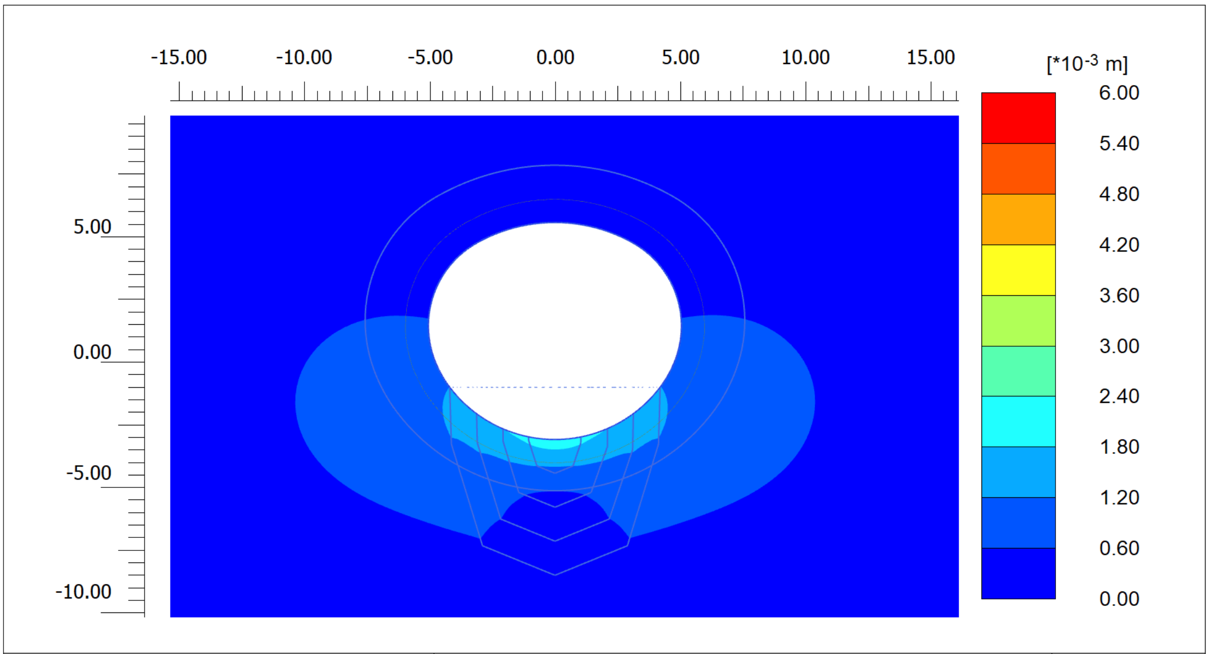

Fig. 4 Total displacements by applying the volumetric strain approach. The full swelling strain of 2.1% is applied in the center, and decreased outwards to 75%, 50%, and 25%, respectively.

The quality of the input parameters used for calculations significantly influences the reliability of the modeling results. One limitation encountered in this study is the insufficient number of laboratory tests available at the time of this study to establish a robust statistical basis for the input parameters. This limitation is further exemplified by the wide range of results obtained, reflecting the inherent variability of the lithology. The interbedded nature of the lithology increases this range even further, since the overall marl to sandstone ratio varies from one sample to another. Regarding the shotcrete properties, the simplified approach of the hypothetical modulus of elasticity after (Pöttler 1990) might influence results over extended periods.

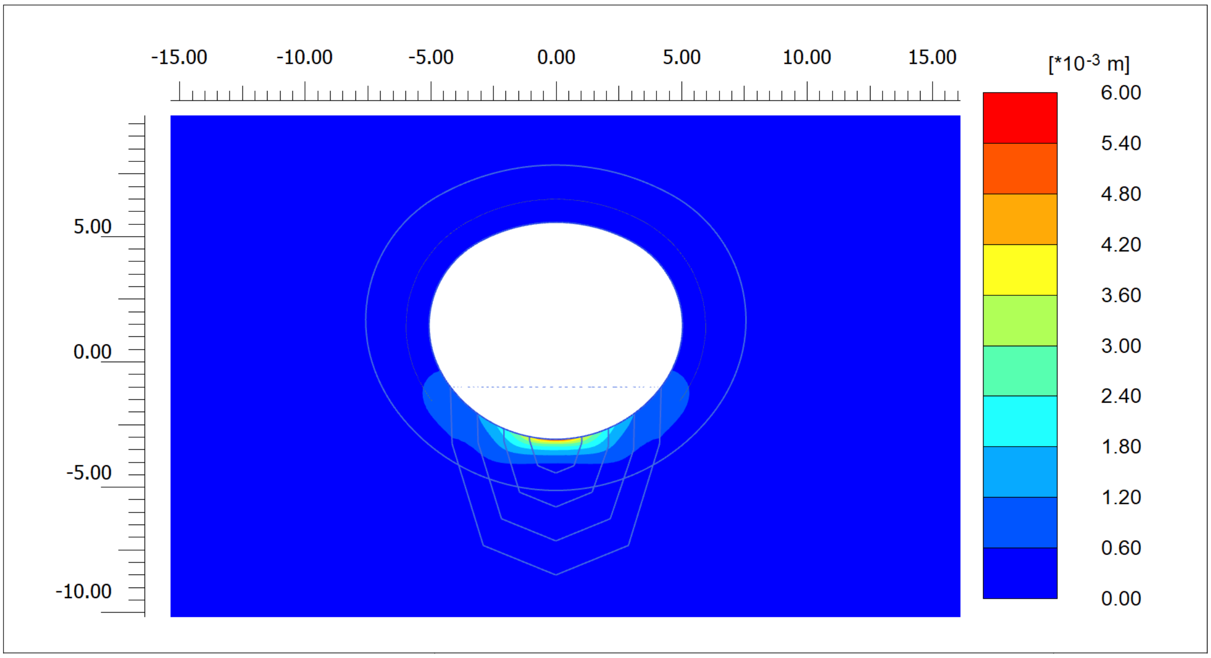

Fig. 5 Total displacements by applying the PLAXIS Swelling Rock Model approach. The full swelling extent from the numerically back-calculated Huder-Amberg test is applied in the center, and decreased outwards to 75%, 50%, and 25%, respectively.

The reduction of the swelling strain approach to 10% of the maximum swelling strain measured in the laboratory test should be mentioned. The 10% value was determined in this study, taking into account a maximum swelling pressure in the range of 300 to 400 kPa for argillaceous swelling. It is therefore questionable whether a value in this range is generally acceptable or whether it varies for each case study.

The consideration of time dependency in modeling poses another challenge. The ability to account for time-dependent behavior varies depending on the employed swelling model, since only the PLAXIS Swelling Rock Model actively incorporates time. Due to the input parameters from the back-calculated axisymmetric swelling test depicted in Fig. 1 it is ensured to work with final displacements in this study. An important consideration for future and more in-depth studies is the selection of a model closely aligning with the observed in-situ behavior to enhance predictive accuracy.

While the 2D modeling approach yields valuable insights into the swelling-induced displacements and stresses, it lacks the ability to fully represent the 3D geometry of the test gallery, particularly the cross-passage stump and the perpendicular alignment of the adjacent tunnel.

5 Conclusion and outlook

The study emphasizes the complexities and limitations of accurately predicting the swelling behavior observed in the Angath test gallery. The simplification of a complex 3D geometry to the 2D model of a cross-section may influence the stress distribution in the model, necessitating further refinement. Also, the interbedded formation of the lithology was simplified as a smeared material in the study. Thus, anisotropic effects due to different material parameter ranges (e.g., strength and stiffness) as well as their interfaces were neglected.

Neither the swelling strain approach nor the more sophisticated PLAXIS Swelling Rock Model is able to model the swelling behavior sufficiently by relying solely on laboratory test results. This emphasizes the need to connect laboratory data with field observations and advanced modeling techniques to enhance predictive accuracy.

To address the limitations identified, future research should also conduct additional laboratory tests to be able to draft statistically drafted and based parameters from the test results. Furthermore, when back calculating laboratory tests, an emphasis on possible interlayers should be placed to incorporate material heterogeneity more accurately. Moreover, predictions of the tunnel behavior should be performed by using all available monitoring results to refine the calibration of numerical models. An extensive focus on the mineralogical composition and possible interactions at micro, meso, and macro scale to apprehend a material's swelling behavior more accurately is recommended.

In addition, future work should consider intermediate time steps between initial and final displacements more closely within the modeling process and possibly employing 3D modeling approaches to better capture spatial interactions and enable a more representative analysis of the complex stress and displacement patterns. Furthermore, employing advanced modeling tools may potentially increase the accuracy and reliability of predictions, since they comprise more comprehensive capabilities for incorporating anisotropy, time dependency, and other geological complexities.

The challenges notwithstanding, this study offers a background that contributes to understanding and improving the modeling of argillaceous rock swelling behavior. Further efforts at refinement of modeling techniques and incorporation of multidisciplinary approaches could be promising in further developing both scientific knowledge as well as practical applications within tunneling and geotechnical engineering.

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