Future Challenges in Tunnel Stability Analysis Using Artificial Intelligence and Machine Learning

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Abstract. Entering the information age, we encounter a huge amount of data, and this big data requires automatic data analysis methods that provide machine learning and deep learning. Machine learning (ML) is a branch of artificial intelligence that is currently developing and evolving and is a very active field in computer science. In general, machine learning is defined as a set of methods that can automatically identify patterns from data and use undiscovered patterns to predict future data or make other types of decisions under uncertainty. This science is actually an interdisciplinary process that uses various sciences to advance its goals, including artificial intelligence, psychology, philosophy, information theory, statistics and probabilities, control theory, etc. The probabilistic approach to machine learning is closely related to the field of data mining but slightly different in focus and terminology. The importance of machine learning becomes valuable when we know where this learning can help people. On the other hand, the environment can change over time, the machine can adapt to it by learning these changes. The tunneling projects generate vast amounts of data on a daily basis, which includes the instrumentation and behavioral measurements of the tunnels, as well as geological data captured during the construction and execution of underground spaces. This data represents a valuable asset in the field of data science, as it can be leveraged for machine learning and predictive modeling purposes. According to available research, the application of machine learning in the field of important geological and geotechnical questions, which is often a very complex and unknown world full of information, can be used to improve the performance of optimal decision making in the future and plans. The main conclusion is that the number of research in this field increases almost exponentially and the most used (AI) technique is the Artificial Neural Network, and therefore lack of centralized Geotechnical data and datasets is one of the important challenges in Machine Learning and Deep Learning (DL).

Keywords: Machine Learning · Tunnel Stability Analysis · Geotechnics

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1 Introduction

1.1 Data Science in Geotechnical Engineering

The advent of the information age has brought with it an unprecedented amount of data, which requires efficient and automatic methods of analysis. Machine learning is a rapidly growing and evolving branch of artificial intelligence that offers a solution to this challenge.

Machine learning is defined as a set of methods that can automatically identify algorithms from data, and make predictions or decisions based on previously undiscovered patterns. This science is an interdisciplinary field that draws from various sciences such as artificial intelligence, psychology, philosophy, information theory, statistics, control theory, etc. Its applications are diverse and span across numerous fields, such as data mining, pattern recognition, bioinformatics, web page search engines, machine vision, natural language processing, medical diagnostics, stock market analysis, voice and handwriting recognition, software engineering, robot control, etc.

Machine learning's probabilistic approach is closely related to the field of statistics, but with a slightly different emphasis and terminology. The true value of machine learning lies in its ability to help humans in areas where they may lack knowledge or face unknown challenges. For example, in geological environments, where designers may not have all the information about rock and soil behavior, machine learning can learn and adapt over time to changes in the environment.

The field of geotechnical engineering, particularly tunnel stability analysis, is an area where machine learning can be used to make optimal decisions. The vast amount of data produced daily using the New Austrian Tunneling Method (NATM) is a valuable asset that can be utilized for machine learning purposes. This data includes instrumentation and behavior measurements of tunnels, along with geological data collected during excavation. Despite this wealth of information, the uncertainty inherent in the data presents challenges for machine learning, including predicting future data, finding the best model to explain the data, and determining the next steps in measurement.

In this research, an overview of the research on applications of artificial intelligence and machine learning in various geotechnical fields, especially in the field of underground structures engineering with the challenges and advances of using machine learning to analyze tunnel stability is presented. The aim is to discuss and evaluate the potential and future applications of machine learning and deep learning in geotechnics.

1.2 Data Challenge in Geotechnical Engineering

- **Data sources:** For the design of underground structures and in general geotechnical studies, data is often collected from various sources such as geophysical surveys, exploratory well logs, field sampling, laboratory tests, geological field surveys and numerical models. Since these data have different sources and agents, they may lead to data quality fluctuations.
- **Data variability:** Geotechnical data is often very variable and influenced by various factors such as soil type, lithology, groundwater condition, regional geology, tectonic condition, etc. Therefore, uncertainty in geotechnical analysis is an undeniable issue.

- **Data integration:** Centralizing data for small purposes is not a major complication, but when dealing with large and complex data sets, integrating data from different sources can be challenging. Data integration requires standardization of data collection methods, format and measurement units to ensure data consistency. In addition, data integration requires the development of efficient data management systems that can handle large volumes of data.
- **Interpretation and presentation of data:** What is important for geotechnical engineers is to present geotechnical data in a meaningful and interpretable manner, especially when dealing with complex data sets such as 3D data, time series data, and high variability data. Therefore, the ability of the structure of geotechnical engineers to data science engineering and the presentation and display of existing data in the field of geotechnics, in a way that can be used by data scientists, is one of the most important challenges of data interpretation and display.
- **Analytical data methods**: due to the variety of geotechnical data as well as the variety in the purpose of using this data and due to the large volume of collected data, traditional statistical methods may not be suitable for their analysis. To solve this challenge, the development of analytical methods of data science has had a significant speed in recent years. Therefore, they use advanced data analysis techniques such as machine learning, artificial intelligence and data science to better understand data and make predictions. These techniques allow geotechnical engineers to identify patterns and relationships in the data that may not be detectable using traditional methods.
- **High dimensionality:** The issue with geotechnical data pertains to their large dimensionality, implying that geotechnical analyses did influenced by a wide array of factors. For instance, soil parameters like particle size distribution, ductility, and permeability each encompass several parameters that necessitate consideration during analysis.
- **Complex Relationships:** Geotechnical data can have complex relationships and interactions that are not immediately apparent. For example, soil properties such as shear strength and compressibility could be affected by a variety of factors, including soil type, density, moisture content, and temperature.
- **Data management:** One of the most important problems and challenges in geotechnical data, which are often stored in different formats, is data access and management. Therefore, the design and organization of a data management systems that can manage and organize a large amount of data and guarantee data security and data protection is necessary. These systems should also be easy to use for researchers and geotechnical engineers to easily retrieve and manage their data.

To overcome these challenges, the development of more advanced data analysis techniques such as machine learning, artificial intelligence and Deep Learning is needed. These techniques help geotechnical researchers to identify patterns in the data that are often not directly visible using traditional methods. In addition, data visualization techniques to present data in a meaningful and interpretable manner help geotechnical engineers to better understand the data and make valuable decisions.

1.3 Role of Monitored Data in the Underground Space Engineering

As explained in detail in the previous sections, due to the complexity and in homogeneities of the geological and geotechnical characteristics of the single layers, determining values of the parameters of the soil (including geological structures, geomechanical characteristics of rocks, initial state stress, groundwater condition, permeability, etc.) with high accuracy is very difficult and expensive. Analyzing the stability of tunnels and determining the behavioral characteristics of the rock mass using numerical methods such as finite element, boundary element and discrete element are strongly related to the quality of the input data and are therefore subjected to limitations concerning the output data. One of practical method to solve these problems is the use of monitoring and instrumentation system in tunnels, which aims to measure displacements and to validate the assumed underground structures and rock mass characteristics. The data obtained from this monitoring system plays an important role in underground space engineering, because it provides valuable information about the behavior and performance of underground structures. The following are some of the keyways monitoring data be used in subsurface engineering:

- **Control of the parameters used in the analysis:** The discrepancy between the structural behavior observed during implementation, including the degree of convergence, structural behavior, and pressures exerted on the structure, and the predicted values from the analysis represent an anomaly. This anomaly indicates that the data used during the study phase parameters do not match the actual situation. To address this issue, a precision instrumentation system be used to recalculate the parameters. The resulting data are essential for regulating parameters and maintaining structural stability.
- **Evaluation and control of the safety of the structure:** As mentioned, the nonconformity of the measured and during the design prognoses displacement of the structure can affect the stability and safety of the structure. Therefore, by monitoring the deformation of the structure, it is possible to detect possible risks that might threaten the structure.

Hence, the information derived from the measurement and monitoring system plays a crucial role in the construction process of the project, specifically for the underground structures. Owing to the extensive volume of data that is obtainable through the collection of data at various time intervals and locations, this information can hold significant importance in the realm of data science, particularly for machine learning and deep learning applications.

By combining and feeding these data to the machine learning algorithms, it will be possible to have behavioral models, which in the current state of identification might not be possible or expensive for humans.

2 Machine Learning Approaches for Predictive Modeling of Rock Engineering Properties in the Underground Spaces

2.1 Data Sciences Research Fields and Their Fundamental Explanations

In recent years, the use of ML has grown tremendously due to advances in computing power, measurement technology, and data storage. In geotechnical engineering, machine learning extends the traditional observational approach by using data analysis and pattern recognition techniques, assuming sufficient data to describe the physics of the modeled system. Studies have shown that these observational techniques have the potential to save time and money over traditional designs.

Artificial intelligence 'AI', Machine Learning 'ML' and Deep Learning 'DL' are three terms that are often used interchangeably to describe software that behaves intelligently.

- **Artificial intelligence:** Artificial intelligence is a branch of computer science whose main goal is to produce intelligent machines that have the ability to perform tasks that require human intelligence [2]. Artificial intelligence is actually a kind of simulation of human intelligence for computers, and has the ability to imitate human behavior. This definition applied to all machines that act like the human mind and are able to do tasks such as problem solving and learning.
- **Machine learning:** Machine learning is subset of artificial intelligence that enables systems to learn and perform certain tasks automatically without explicit programming [3]. The most common implementation of ML is to establish relationships between inputs and outputs. This method of data science is divided into different methods such as supervised learning process, unsupervised learning, semi-supervised learning and reinforcement learning.
- **Deep Learning:** Deep learning is another subset of ML that uses a special ML algorithm called Deep Artificial Neural Networks (ANN) with many hidden layers to learn from large amounts of data [4].

One of the biggest challenges that has overshadowed machine learning and deep learning techniques is the need for a large database of high-quality information to accurately capture the behavior of the system being modeled. The size of the dataset required for the training process strongly depends on the type of ML technique used, its intended role (such as interpolation, optimization, prediction) and the complexity of the input-output relationship.

3 History of AI and Machine Learning in Geotechnical Engineering

Ahmed M. [4] conducted a review and analysis of research studies in the field of geotechnical engineering that utilized AI techniques. He analyzed 626 papers and theses published from 1984 to 2019, collecting and organizing data on the subject matter; AI techniques used, publisher, and publication date, and stored the findings in a database.

The results of the analysis showed an exponential increase in the number of research studies in this field, with the use of AI techniques becoming increasingly popular. The most commonly used AI technique was Artificial Neural Networks and its variations, which accounted for approximately 50% of the research studies. The most frequently addressed subject in these studies was the correlation between soil and rock properties, accounting for approximately 30% of the research.

This review highlights the significant development and growth in the field of geotechnical engineering utilizing AI techniques. It is evident that AI has the potential to provide valuable solutions for the challenges faced in this field and is becoming increasingly integrated into the work of geotechnical engineers. The trend of using AI techniques in geotechnical engineering research is likely to continue and advance further, leading to new and innovative solutions for the industry.

3.1 Utilize of Machine Learning in the Underground Engineering

The application of artificial intelligence (AI) in the field of civil engineering of underground structures was researched and evaluated. While the interaction between surrounding soil and tunnels and underground structures is often complex, the use of artificial intelligence techniques is seen as a possible solution to this problem. However, compared to other application fields of artificial intelligence, the field of civil engineering has only made a limited contribution so far.

The studies conducted by Ahmed show that out of 916 cases of artificial intelligence applications in the geotechnical field, only 34 cases (less than 4%) are related to the construction of underground structures.

The application of artificial intelligence in tunnelling focuses on three key areas:

- prediction of land subsidence due to tunnel excavations,
- Selection of the optimal tunnelling method based on the properties of the soil and the thickness of the tunnel cover,
- Eestimate the stresses and deformations of the coating.

This difference in application illustrates the challenges in the field of geotechnical engineering, but also shows potential for future research. In order to exploit this potential, access to necessary information such as geotechnical data, engineering geological data and tunnel monitoring data is of crucial importance. This is only possible by setting up a global geotechnical database and a central data management system. Therefore, the application of artificial intelligence in the field of underground building construction is still in its infancy, the potential for future contributions is significant. With access to the necessary information and resources, this field can continue to advance and to improve current techniques and practices (Fig. 1).

4 Conclusion

Artificial Neural Networks (ANN) have been popular due to their ability to capture complex nonlinear relationships, but in recent years, with the growing development of Machine Learning (ML), especially since 2019, the use of these methods among geotechnical researchers is also developing.. Literature review shows that ML is used for tunneling operations such as TBM performance prediction, tunnel settlement prediction, geological prediction, and cutting head design optimization.

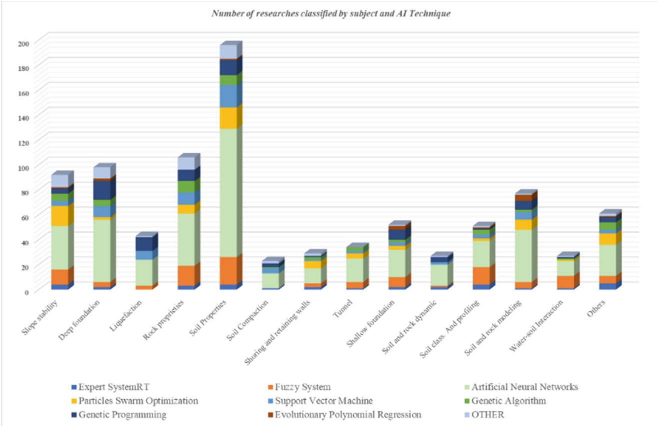

Fig. 1. Comparison Chart of the Utilization of Various Artificial Intelligence Algorithms in Different Fields of Geotechnical Studies.

However, the field of ML in tunneling is still in its infancy and needs further research. Probabilistic frameworks such as Bayesian networks and Gaussian process regression (GPR) are considered promising ML techniques that should be further explored in this field. The studies were developed and validated based on a single case study, which limits their generalizability. To increase the robustness of these techniques, there is a need for further validation in a wider range and the integration of causal modeling in ML.

The tunneling industry can benefit from these advances in ML by considering how these techniques are used during tunneling operations. Consequently, probabilistic ML techniques such as Bayesian networks and GPR are considered the most promising methods for future applications of ML in tunneling operations. As explained above, one of the biggest challenges that has overshadowed machine learning and deep learning techniques is the need for a large database of high-quality information to accurately capture the system being modeled. Therefore, it is inevitable to create a centralized geotechnical data bank to collect and provide transparent and standardized data for future research.

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