

Review

Research Progress of Three-Dimensional Engineering Geological Evaluation Modeling

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Abstract: With the rapid development of China's economic construction and the increasing scale of the project, more and more complex engineering geological problems have put forward higher requirements for engineering geological researchers. As the core link of engineering geological research, engineering geological evaluation provides a key scientific basis for solving engineering geological problems. The engineering geological evaluation model is a good tool and means to support the realization of the evaluation method. Therefore, it is urgent to study three-dimensional engineering geological evaluation modeling systematically. In view of the current situation that the construction methods of the three-dimensional engineering geological evaluation model in the field of infrastructure construction at home and abroad are not uniform, this paper briefly summarizes the research progress of the three-dimensional engineering geological evaluation model. It focuses on three-dimensional geological modeling and the three-dimensional engineering geological space evaluation index system. This study discusses the main methods for comprehensive engineering geological evaluation and the construction of a three-dimensional geological model. At the same time, in response to the low accuracy of current three-dimensional engineering geological evaluation models and their insufficient integration with numerical simulations, this paper proposes improvement suggestions and outlines the development trends of such models. The purpose of this paper is to deepen the engineering geological evaluation work, promote its sustainable development, and lay the foundation for the study of a three-dimensional engineering geological evaluation model so as to cope with more complex engineering geological challenges in the future.

Keywords: engineering geology; three-dimensional geological model; explicit and implicit modeling methods; index system; stereoscopic evaluation



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1. Introduction

Engineering geology is a science that specializes in the interaction between engineering construction and the geological environment. Its core task is to comprehensively evaluate the adaptability of the geological environment before the start of the project and predict the

potential impact of the project on the geological environment and its possible changes, especially the damage to the stability of the building itself and the surrounding environment [1]. These assessments can provide a scientific basis for engineering design, construction, and operation. The fundamental purpose of engineering geological evaluation is to study the influence of engineering disturbance on the geological environment. The results will help the relevant technical personnel to fully grasp the various geological factors affecting the quality of the project and their weight and role in the engineering geological process [2].

Engineering geological evaluation involves a comprehensive analysis of a series of complex factors, including rock mass structure, weathering unloading, geological structure, stratigraphic lithology, dynamic geological action, topographic and geomorphic characteristics, and the impact of engineering facilities (such as roads, rivers, buildings, etc.) on the geological environment. With the continuous and rapid development of China's economic construction and the increasing scale of the project, the engineering geological work is facing unprecedented challenges [3]. For example, the depth of underground mining has exceeded 1500 m, and the depth of oil drilling has exceeded 10910 m. The exploitation of deep resources in kilometers has become the norm. The development and utilization of deep space resources have become a key direction of future human activities. Therefore, it is urgent to adopt more precise and scientific engineering geological evaluation methods [4]. With the wide application of new technologies, such as electronic computing technology, expert systems, numerical simulation, and system engineering analysis, the technical level of engineering geological evaluation has been significantly improved (Figure 1). Especially, under the support of modern mathematical science, the research of the engineering geological evaluation model has made breakthrough progress [3], which has realized the transformation from qualitative research to semi-quantitative and quantitative research and gradually constructed a perfect theoretical system of engineering geological evaluation [5].

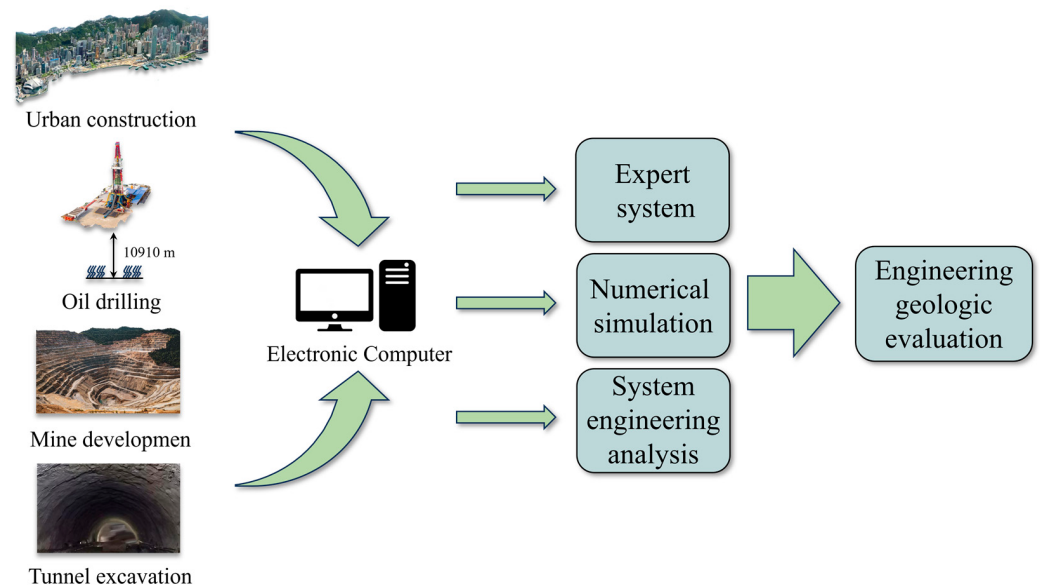


Figure 1. Promoting effects of emerging technologies on engineering geological evaluation.

In this context, the engineering geological evaluation model, as an important tool to realize the quantitative evaluation of engineering geology, has become the core support of engineering geological analysis. The engineering geological evaluation model is based on the principles of scientific analysis and systematic thinking. Through digital processing and information transmission and conversion, physical engineering geological information is transformed into a visual image tool. It is an important means to realize the quantitative evaluation of engineering geology and provides the core support for engineering geological

analysis. Its role is not only reflected in the efficient organization of information in the evaluation process but also through the combination with the information transmission theory of cartography, the complete chain from digital information to visual expression is realized [6]. The research on engineering geological evaluation models mainly involves two dimensions: two-dimensional and three-dimensional. For example, Wang et al. proposed the Development Potential of Urban Underground Space (DPUUS) model, which explores the key factors influencing the development of urban underground space from a two-dimensional perspective [7]. On the other hand, Zhou et al. used ArcGIS (Esri, Redlands, CA, USA) software to assess the development potential of urban underground resources from a three-dimensional perspective, contributing to the sustainability of urban development [8]. The traditional two-dimensional evaluation method integrates the engineering geological factors at different depths and divides the grid on the plane to calculate the suitability of the area. However, this method has limitations in dealing with complex spatial structures and often leads to the loss of depth information (Figure 2), which cannot fully reflect the spatial heterogeneity of engineering geological conditions [9].

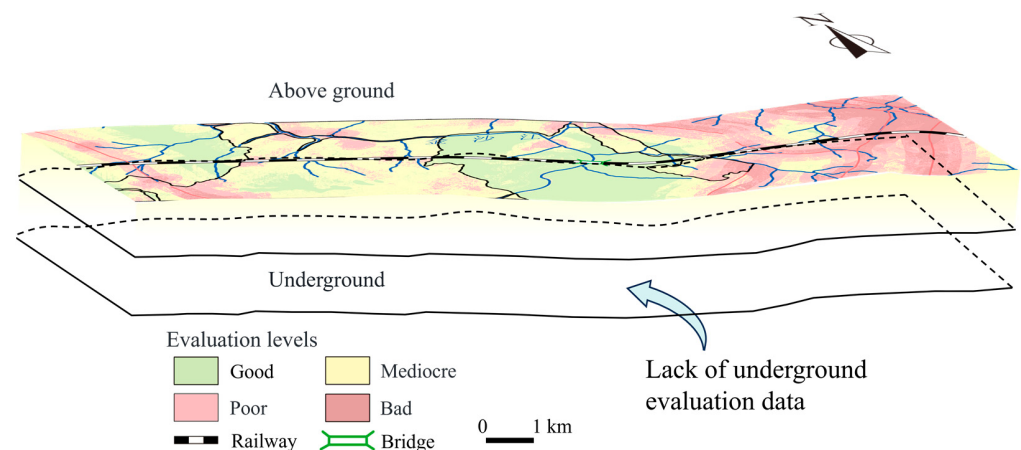


Figure 2. Data missing in the two-dimensional evaluation graph.

In recent years, three-dimensional geological modeling [10], three-dimensional geographic information systems [11], and building information model technology [12] have achieved rapid development and have been widely used in engineering practice. These technologies provide a variety of technical means for the visualization of three-dimensional data by systematically sorting and analyzing multi-source data and establishing three-dimensional models [10]. By integrating multiple data sources, the three-dimensional engineering geological evaluation model can not only present the analysis results intuitively but also provide strong help for the design and construction of the project. The evaluation model can effectively predict the potential risks under complex geological conditions and can be applied to water conservancy and hydropower, railway construction, urban development, mining, and other fields. By evaluating the key engineering geological parameters, the three-dimensional engineering geological evaluation model provides a high-quality decision-making basis for engineering planning and design, helps to avoid unfavorable geological conditions, promotes the rational use of land resources, and realizes the coordinated development of engineering construction and geological environment [11].

Compared with the traditional two-dimensional evaluation method, the three-dimensional engineering geological evaluation method can describe the spatial distribution of geological attributes at different depths in more detail and can also intuitively show the change in engineering geological suitability in three-dimensional space. The evaluation model can more accurately reveal the differences in engineering geological suitability at different spatial scales and provide more accurate and comprehensive data information

for the scientific planning of engineering design and construction. The theory, method, and related software of three-dimensional engineering geological evaluation modeling have laid a solid foundation for the construction of modern three-dimensional engineering geological evaluation models. This paper systematically summarizes the research processes in the field of three-dimensional engineering geological evaluation modeling in recent years and gives a set of evaluation modeling processes suitable for this field. In response to the low accuracy of current three-dimensional engineering geological evaluation models, this paper proposes improvement strategies and outlines future development directions for these models. This study not only provides theoretical guidance and technical support for the construction of a three-dimensional engineering geological evaluation model but also lays a solid foundation for promoting the wide application of three-dimensional engineering geological evaluation technology, which has important academic value and practical significance.

2. Methods

The essence of the three-dimensional engineering geological evaluation model is to combine the engineering geological evaluation results with the three-dimensional geological model. Through the systematic calculation and analysis of the geological evaluation factors that have an important influence on the project, such as rock mass structure, geological structure, stratigraphic lithology, dynamic geological action, and topographic and geomorphological characteristics in the study area, the evaluation results are substituted into the three-dimensional geological model. This model not only makes the expression of geological information more refined and three-dimensional but also provides a basis for professionals in related fields to meet engineering calculation, prediction analysis, and decision making under different needs.

In recent years, with the rapid development of three-dimensional geological modeling technology, the study of the three-dimensional engineering geological evaluation model has gradually formed a relatively complete technical system. This system mainly includes the following key links. (1) The construction of a three-dimensional geological structure model, in which, based on geological information, a three-dimensional geological structure model that accurately reflects the geological conditions of the study area is established. (2) The construction of a three-dimensional spatial evaluation index system, in which, according to the engineering requirements, a three-dimensional comprehensive evaluation index system covering various influencing factors such as rock and soil strength, physical parameters, and geological structure is established. (3) The engineering geological comprehensive evaluation method, in which, through the calculation of the selected three-dimensional index weight factor, the engineering geological conditions of the study area are comprehensively evaluated. (4) Based on the evaluation results and the three-dimensional geological model, a three-dimensional engineering geological evaluation model is constructed.

2.1. The Establishment of the Three-Dimensional Geological Model

With the rapid development of modern computing technology, three-dimensional geological modeling technology has become the core means to deal with the storage, processing, display, and analysis of increasingly massive geological data [13], and it is also an important research direction in the field of engineering geology [14]. The three-dimensional geological model not only accurately depicts the geometric relationships of rock strata, the internal composition of geological objects, and their spatial-temporal evolution characteristics [15] but also serves to predict the engineering geological properties and hydrogeological characteristics within the study area [14]. The three-dimensional geological model can visually present the distribution of strata and structural planes in space,

providing engineers with a powerful and convenient tool to help them deeply analyze the relationship between engineering structures and unfavorable geological conditions. The three-dimensional digital geological framework model proposed by the British Geological Survey is a representative and innovative achievement in the field [16] and successfully constructed the three-dimensional geological models of the surface and bedrock in the London Basin [17]. Three-dimensional geological modeling technology combines computer graphics and geology. Through mathematical methods and geological laws, the geometric shape contour of geological bodies is constructed as a three-dimensional model to describe the distribution of geological physical parameters in space accurately.

The process of three-dimensional geological modeling usually includes two main stages: data collection and modeling (Figure 3). In terms of modeling methods, three-dimensional geological modeling can be divided into two types: explicit modeling and implicit modeling [18]. These methods have their characteristics and adapt to different geological conditions and data types, aiming to provide more accurate three-dimensional geological representation and reliable data support for subsequent engineering analysis and decision making [19].

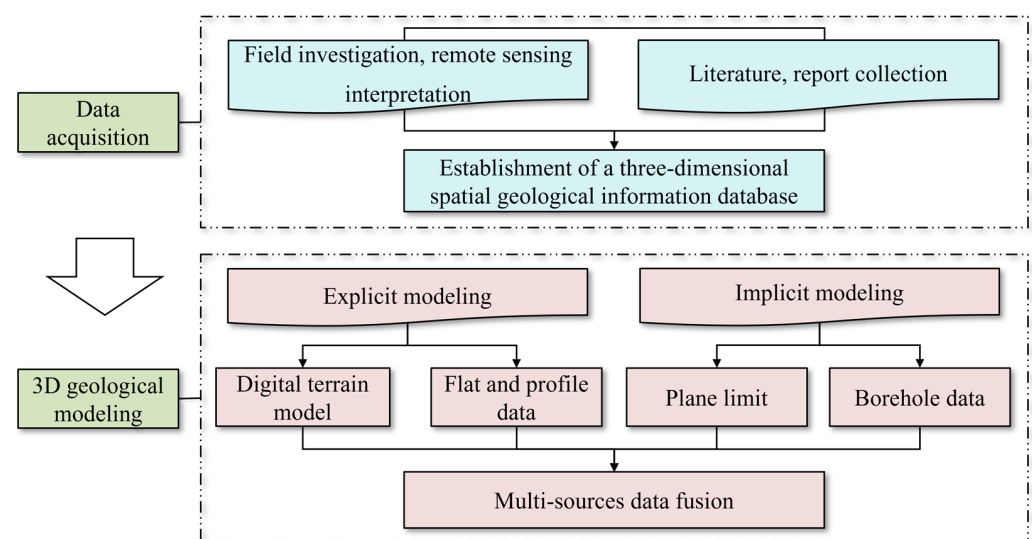


Figure 3. The main process of 3D (three-dimensional) geological modeling.

(1) Explicit modeling. The explicit modeling method is based on the geometric coordinates and occurrence data obtained from geological surveys and exploration and constructs geological bodies according to certain rules [19]. In the process of modeling, a closed geological interface is gradually constructed by describing the topological relationship of spatial geometric objects. This process involves complex geometric intersection and cutting and closing operations, and it also needs to deal with technical challenges, such as computer floating point error processing (Figure 4). The main advantage of explicit modeling is the operability of the model, but its disadvantage is that the multi-source heterogeneous data fusion ability is weak, and the data update requires large-scale reconstruction of the model, which is time consuming and laborious. Explicit modeling is often used in the division of geological units, which is suitable for detailed modeling of small-scale and specific geological units. Through the topological relationship between the spatial elements of the section, a three-dimensional geological model is generated. This method requires sufficient pre-data preparation and a high level of geological knowledge of the modeler. The modeling accuracy depends on the profile accuracy, the amount of profile data, and the knowledge level of the modeler. Although the modeling rate is relatively low, complex geological models can be established.

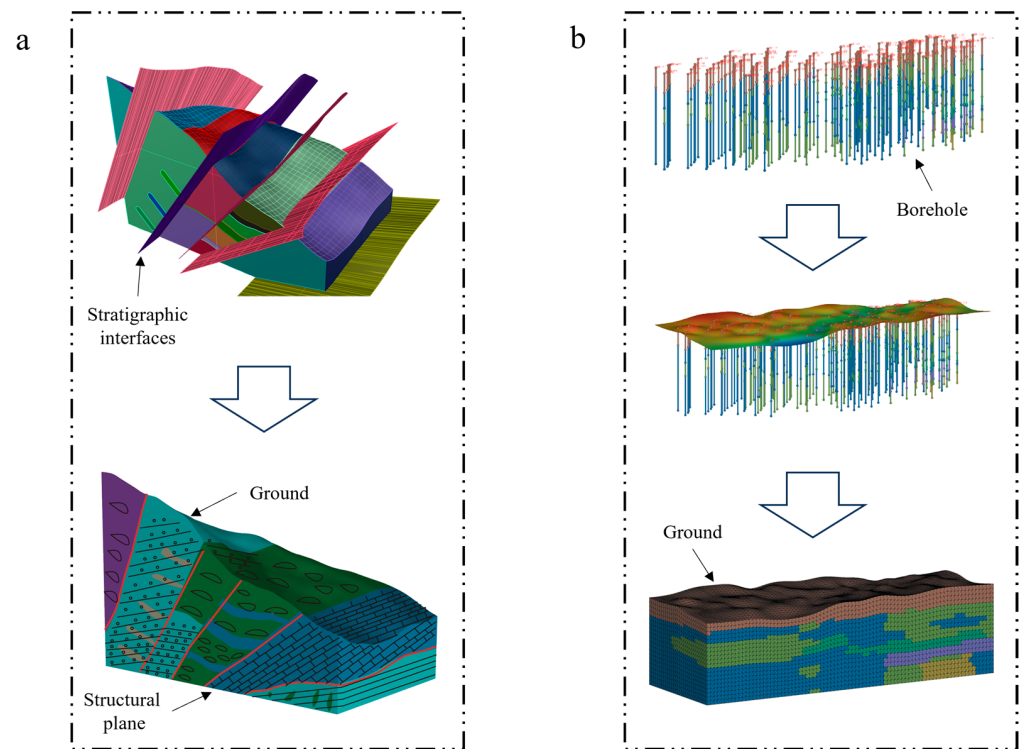


Figure 4. Explicit–implicit modeling process: (a) explicit modeling method; (b) implicit modeling method ((b) is modified from [20]).

(2) Implicit modeling. Implicit modeling is based on spatial sampling data through spatial interpolation to construct the implicit function expression of a three-dimensional solid surface (i.e., $f(x, y, z) = 0$) [21]. Implicit modeling does not need to draw each geological interface in detail, and its core idea is to describe the shape and distribution of geological bodies through mathematical models. The specific logic is that by filling the area to be modeled into a regular hexahedral grid [19], the known data are mapped to the grid as a sample of spatial interpolation, and the geometric shape of the geological body is constructed by interpolation algorithm (Figure 4). Its core lies in the interpolation algorithm. At present, Kriging interpolation, discrete smooth interpolation, and inverse distance ratio methods are mainly used. Compared with explicit modeling, implicit modeling does not require human–computer interaction and is simple to operate. It significantly improves the efficiency of modeling, avoids the cumbersome operation of dealing with complex geological interfaces in explicit modeling, and makes it easier to integrate multiple geophysical and geological data sources. Implicit modeling is especially suitable for large-scale and high-precision model construction scenarios, but the interpolation effect may be poor when the sample points are scarce or the number of spatial grids is too large. In general, in the field of engineering geology, implicit modeling is mostly used for engineering geological analysis and resource exploration and evaluation, while explicit modeling is used for the subdivision of local geological units (Table 1).

Table 1. Comparison of explicit modeling and implicit modeling.

Contrast Dimension	Explicit Modeling	Implicit Modeling
Method	Geological body contour line connection method based on sequence exploration line profile	Interpolation algorithm
Precision	Higher (relying on expert experience)	General (depending on the quality and quantity of borehole data)
Difficulty in operation	Difficult	Easy
The difficulty of updating data	Difficult	Easy
Applicable scene	Engineering geological modeling and construction of engineering geological interface	Engineering geological analysis, resource exploration, and evaluation

In addition, the multi-source data fusion modeling combining explicit modeling and implicit modeling realizes the optimization of geological model construction [22]. In this method, geological units are first divided by explicit modeling, and then based on implicit modeling technology, borehole data are effectively integrated to generate a complete three-dimensional geological model automatically. This process integrates a variety of geological data types, including borehole data, profile data, plane geological maps, geophysical and geochemical anomaly contours, etc., and uses human–computer interaction mode for data processing and modeling. According to different types of geological bodies, appropriate modeling methods are selected. Finally, through multi-model fusion technology, the accurate modeling of complex geological bodies is completed, and the interaction of multi-source data is realized.

Globally, scholars from various countries have conducted three-dimensional geological modeling using a variety of software programs. These include EVS (Earth Volumetric Studio) (C Tech, Cooper City, FL, USA), GeoModeller™ (Intrepid Geophysics, Sydney, Australia), DepthInsight (Grid World, Beijing, China), Civil 3D (Autodesk, San Rafael, CA, USA), GoCAD™ (Geovariances, Paris, France), Leapfrog Works (Seequent, Wellington, New Zealand), and Creatar Xmodel (Creatar, Beijing, China). EVS software is based on the indicator Kriging method for geological modeling and realizes lithology division by calculating the probability distribution of different lithologies in space, which is suitable for the construction of the three-dimensional model under complex geological conditions. Cheng et al. used the three-dimensional modeling analysis software EVS based on the GIK (Geology Indicator Kriging) geological modeling function of the indicator Kriging method to realize the rapid construction of the three-dimensional geological model under complex geological conditions [20]. GeoModeller™ uses the co-Kriging method to construct an implicit three-dimensional geological model, which is especially suitable for sedimentary strata modeling. It supports multi-source integration and updates of geological maps, profiles, boreholes, and geophysical data, and it can quickly generate fine geological models [9].

Depthinsight is developed by Beijing Grid World Company. It uses a truncated rectangular grid and an ordinary co-Kriging method to divide the area into high-density three-dimensional grids to ensure the continuity and smoothness of the formation interface. Based on Surpac (Geovia, Paris, France) software, Li et al. established a database of geological bodies in the mining area and used the database to carry out three-dimensional geological modeling of Haiti gold deposits [23]. The Creatar Xmodel platform has been successfully applied to geological modeling within 50 m underground in Beijing (Figure 5) [24].

Through the grid processing of engineering geological and hydrogeological data in this area, a high-precision geological model containing more than 1.28 million evaluation units is generated, which has become an important tool for engineers to analyze geological conditions and identify risks. The GoCAD™ 3D geological modeling software has also been applied in regional-scale 3D geological modeling of the Kondamine River Basin in Australia, using a multi-source data modeling approach to further improve the accuracy of the geological model [25]. In Italy, Giacomelli et al. reinterpreted borehole data based on lithofacies information and successfully constructed a 3D geological model of the Bologna region using Leapfrog Works 3.1 software [26]. Similarly, Yevalla et al. combined resistivity survey techniques with the implicit modeling function of Leapfrog Geo 5.1.4 (Seequent, Wellington, New Zealand) software to generate a 3D geological model of the Kribi area in Cameroon [27].

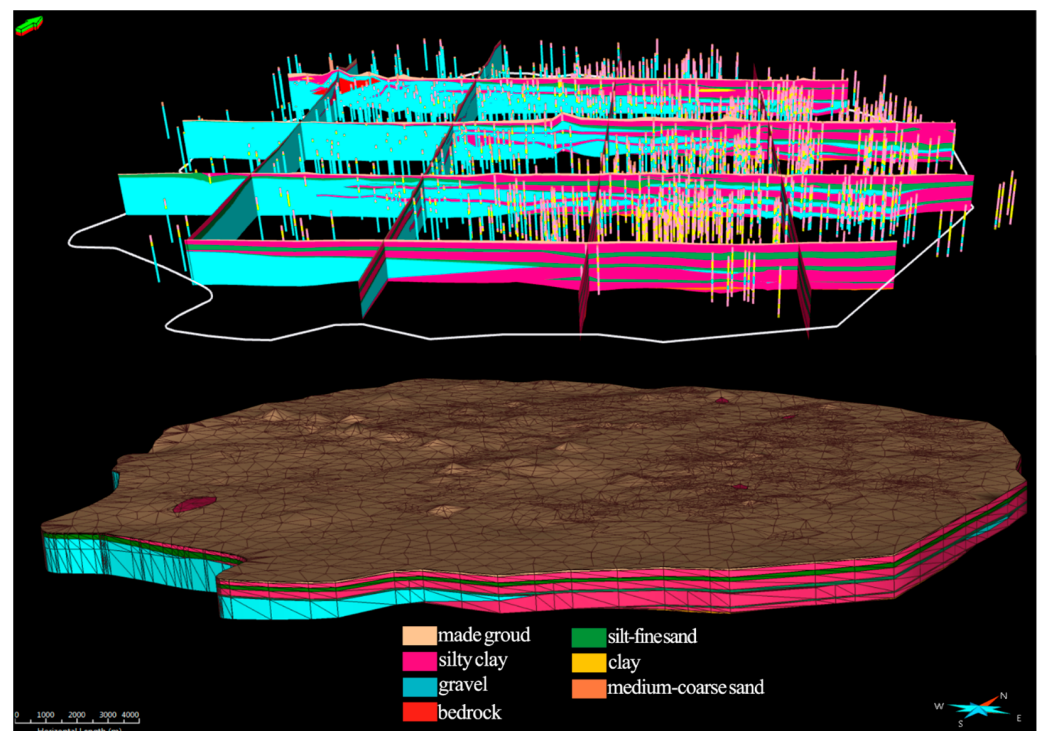


Figure 5. An example of three-dimensional geological modeling in Beijing, China [24].

Due to the inherent uncertainty of stratum type and geological attribute [28], the accuracy of the geological section is limited, and the drilling data are often incomplete, which makes the interpolation algorithm have obvious limitations in accuracy and applicability [29]. The accuracy of three-dimensional geological models significantly influences the precision of the evaluation results. Therefore, properly characterizing the uncertainty features of three-dimensional geological models is essential for enhancing the reliability of the model output results [30]. The sources of uncertainty in geological models can be broadly divided into subjective and objective factors. Subjective uncertainty can be effectively mitigated by applying professional geological knowledge and standards, which helps reduce interpretative errors and thereby decrease uncertainty in interpretation [31]. Høyer et al. proposed and discussed methods for qualitative uncertainty assessment, systematically summarizing the uncertainty chain within the geological modeling workflow [32]. They further demonstrated the primary sources of data uncertainty through practical modeling examples from two different model regions. Several researchers have utilized methods such as information entropy, Bayesian theory, and Monte Carlo uncertainty estimation (MCUE) to reduce uncertainty in geological modeling from an objective

standpoint. For example, Wellmann et al. conducted a quantitative study on the uncertainty of three-dimensional geological models using information entropy [33]. González-García et al. employed a stochastic method based on Bézier curves to assess geological uncertainty in the Ruiz-Tolima Volcanic Massif (Colombia) [34]. Pakyuz-Charrier et al. optimized the Monte Carlo Uncertainty Estimation (MCUE) method and utilized Bayesian theory to parameterize disturbance distributions, effectively improving the reliability of geological modeling uncertainty [35]. Olierook et al., using the Bayesian Obsidian software, integrated field survey data with remote sensing geophysical data and proposed a method for three-dimensional characterization of shallow subsurface geological uncertainty [36]. Zhao et al. used Conditional Random Fields theory and Markov Chain Monte Carlo methods to characterize stratigraphic uncertainty and conducted a case study at a site in Western Australia [29]. Sun et al. iterated the data based on the Monte Carlo method and in combination with the theory of particle swarm optimization algorithm, achieving efficient prediction of the fracture grid in the unknown region [37]. Based on multi-source geological information, Huang et al., through the Bayesian framework, established a comprehensive probability model and finely reconstructed the three-dimensional geological model of deep faults [38]. Liu et al. proposed a three-dimensional modeling method that combines a pixel bi-directional long short-term memory (bi-LSTM) network and random field theory, achieving probabilistic stratigraphic modeling of limited borehole data [39]. Yan et al. proposed an adjustable probabilistic three-dimensional geological modeling method, which iteratively refines the model based on the collected data, reducing the uncertainty of the three-dimensional geological model [40].

In addition, the integration of artificial intelligence technology has brought new development opportunities for three-dimensional geological modeling. By integrating intelligent components, high-precision sensors, and real-time monitoring of geological data, and with the help of advanced data management platforms, it is possible to continuously update and optimize geological models. Feng et al. established a deep learning-based recognition model to intelligently extract borehole data, structural surface morphology, faults, and other three-dimensional information, enabling three-dimensional reconstruction of the model [41]. Pan et al. proposed a three-dimensional intelligent fracture identification and semi-automatic extraction method, achieving intelligent recognition of fracture parameters and three-dimensional reconstruction, with promising results in both laboratory and real-world engineering applications [42]. Artificial intelligence modeling has greatly enhanced the reliability and accuracy of three-dimensional geological models, enabling them to more agilely adapt to dynamic changes in geological conditions, thereby significantly improving the accuracy of risk prediction and engineering assessment. In conclusion, scholars both domestically and internationally generally favor multi-source data fusion modeling methods, as these approaches offer significant advantages in improving model accuracy and enhancing their reference value.

2.2. Construction of the Three-Dimensional Space Evaluation Index System

The core of engineering geological evaluation is to systematically analyze the regional engineering geological conditions, reasonably screen out the geological factors that have a key impact on the construction of the project, and clarify the degree of influence [2]. The evaluation index system is a complex system, which involves the interaction between the key factors in engineering geological conditions, including topography, geotechnical engineering properties, and spatial structure characteristics of geological bodies. A complete evaluation system usually consists of four parts: evaluation object, first-level index, second-level index, and evaluation result (Figure 6).

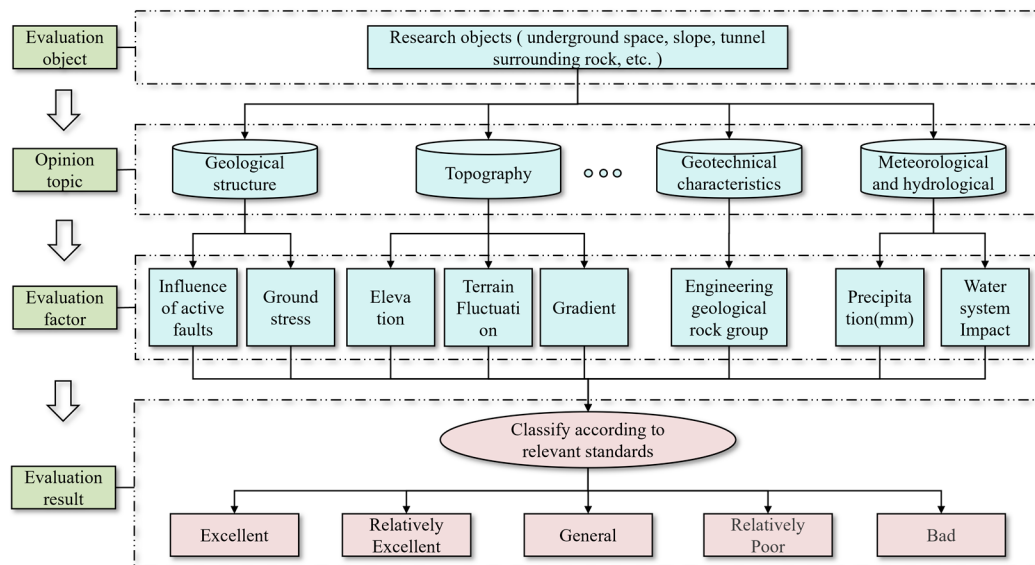


Figure 6. The engineering geological evaluation index system.

The three-dimensional engineering geological model is constructed, and the evaluation process is introduced. Compared with the two-dimensional evaluation system, the three-dimensional evaluation system has significant advantages, mainly reflected in its ability to comprehensively consider more influencing factors and provide more intuitive and comprehensive expression. Specifically, the three-dimensional model can show the depth change in geological characteristics in the spatial dimension (Figure 7) [9] to more clearly reflect the engineering geological evaluation results at different depth levels. The selection of evaluation indexes should follow the principles of systematicness, hierarchy, scientificity, and practicability, and reasonable indexes should be selected according to the actual situation of the study area [43].

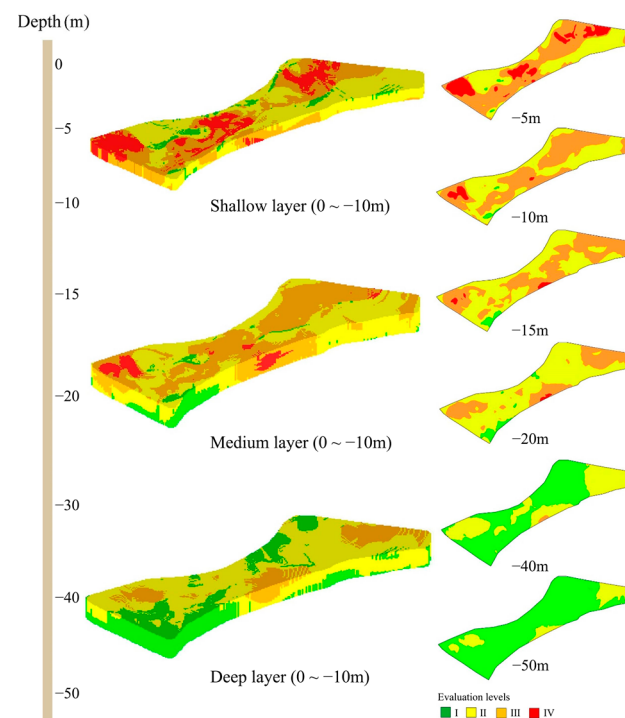


Figure 7. Evaluation of the three-dimensional engineering geological model of Qianjiang New Town in China at different depths [9].

The construction of the evaluation index system needs to be systematic. It should not only cover the control factors that are beneficial to the construction of the project but also reflect the limiting factors that are highly sensitive to the construction of the project and estimate the possible environmental impact after the completion of the project. When selecting the evaluation index, various factors affecting the suitability of the project must be considered, and a comprehensive analysis should be carried out in combination with the three-dimensional geological conditions. The corresponding mathematical methods are used to determine the weight of each index factor, quantify and classify, to realize the qualitative or quantitative judgment of each factor and the overall suitability evaluation results. At present, due to the diversity of engineering types and geological conditions, there is no uniform standard for the selection of evaluation indicators in the engineering and academic circles. Generally, the empirical selection method is used to determine the corresponding evaluation criteria according to different research objects. Different types of specific projects will also lead to differences in suitability evaluation grades [44]. For example, for tunnel engineering, if the tunnel passes through the fracture zone, the differential movement of the fracture may cause vertical deformation and even damage the structural strength. If the horizontal movement of the fault zone occurs, it may lead to shear failure. Therefore, in the process of suitability evaluation of tunnel engineering, the characteristics of three-dimensional fracture activity can be considered as the key engineering influencing factors. For foundation pit engineering, soft soil shows obvious rheological properties. Lateral deformation and shear failure are easy to occur during foundation pit excavation, which will directly affect the overall stability of the supporting structure. Therefore, in the three-dimensional evaluation of foundation pit engineering, attention can be paid to the layout and properties of anchor bolts. In tunnel engineering, the rheology of soft soil may lead to long-term slow deformation of the tunnel. Therefore, the quality of three-dimensional segment splicing and grouting reinforcement should be considered in the evaluation. The following is a brief introduction to several common first-level indicators for engineering geological evaluation (Figure 8).

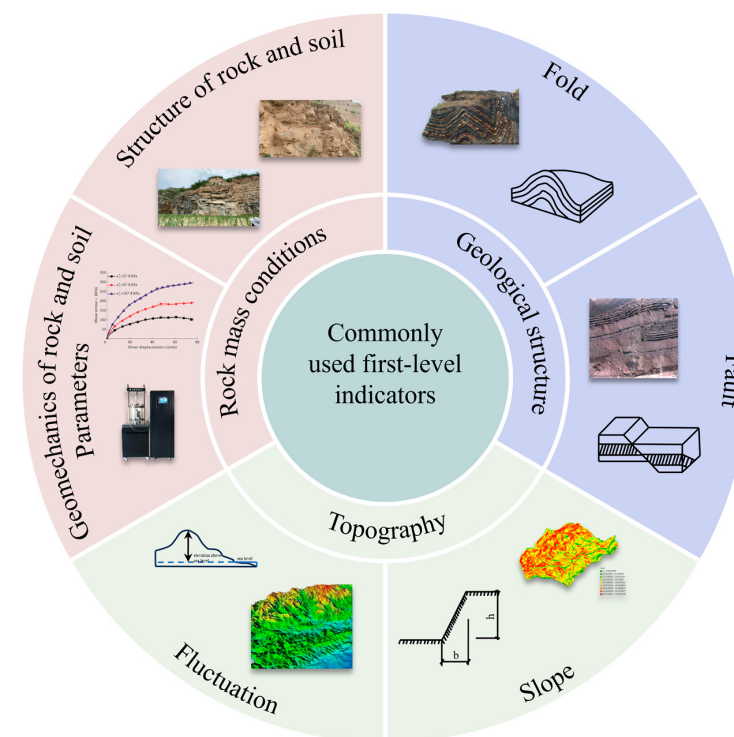


Figure 8. Common indexes affecting engineering geological evaluation.

(1) Rock and soil conditions. Rock and soil conditions are closely related to the safety and stability of engineering construction. The key parameters include void ratio, compression coefficient, compression modulus, cohesion, and internal friction angle. These parameters are not only the key to two-dimensional evaluation but also should be combined with the spatial distribution characteristics of rock and soil in the three-dimensional geological model to comprehensively evaluate [9]. The smaller the void ratio is, the higher the structural strength of the rock and soil mass is, while the larger compression coefficient and modulus indicate that the rock and soil mass has good deformation resistance. Cohesion and the internal friction angle determine the shear strength and bearing capacity of rock and soil. In addition, the brittleness of rock also affects the safety of engineering geology [45].

(2) Topography. Topography, as the basis of engineering geological evaluation, can reflect the overall characteristics of the site and directly affect the design and construction of engineering facilities in three-dimensional space. Because the acquisition of borehole lithology and shear wave velocity requires a lot of manpower and material resources, it is usually estimated indirectly by topographic features (such as slope and altitude). For example, Wald et al. proposed that slope can be used as a classification criterion for sites [46].

(3) Geological structure. Geological structure (such as the fault) will affect the stability of the geological body, thereby affecting the bearing capacity, deformation, and stability of the foundation. The permeability of the fault is significantly different in the vertical and horizontal directions, and the permeability and mechanical properties of the fault zone and the surrounding rock are also quite different [47]. This difference directly affects the hydrological conditions and mechanical response of underground space, which in turn affects the probability of geological disasters and the stability of engineering construction.

Constructing a three-dimensional spatial evaluation index system not only needs to clarify various influencing factors but also needs to rely on a multi-level evaluation system to achieve a systematic quantitative analysis of suitability. The application of a multi-level evaluation system is helpful in classifying and hierarchically displaying the role of various influencing factors and providing scientific support for engineering decision making at all levels. Through this system, the interaction between geological environment characteristics, engineering conditions, and environmental risks can be systematically revealed, which provides a quantitative basis for project risk assessment and design scheme optimization. For example, Zhao et al. systematically evaluated the suitability of Singapore's underground buildings based on geological, hydrological, and environmental factors [48]. According to the relevant criteria, Lu et al. divided the environmental suitability into four grades, poor suitability area, general suitability area, more suitable area, and suitable area, to comprehensively evaluate the suitability of underground space [49]. The classification standard is based on the influence degree of geological environmental impact factors and refers to expert opinions and empirical values to ensure the scientific rationality of the evaluation system. However, there is no uniform classification standard for systematic evaluation in the field of engineering geology. Generally, the evaluation objects are divided into five grades of 'excellent, better, general, poor and poor' according to several evaluation factors [2]. Selecting reasonable evaluation indexes of engineering geological space and adopting scientific quantification and classification methods can provide an effective evaluation method for the construction design of the project. With the deepening of relevant research progress, the evaluation index system of engineering geological space will pay more attention to the comprehensive integration and system analysis of interdisciplinary elements, further improve the accuracy and comprehensiveness of the evaluation results,

and provide more scientific and reliable theoretical support and practical guidance for engineering decision making.

2.3. The Engineering Geology Comprehensive Evaluation Method

The comprehensive evaluation of engineering geology aims to calculate the weight of the selected evaluation factors and analyze the score of each factor in the system. In engineering geological evaluation, the determination of weight is a crucial part of multi-level decision making. Reasonable weight assignment can effectively improve the scientificity and rationality of the evaluation results [50]. If the weight of a factor changes, it will have a significant impact on the overall evaluation results. Therefore, selecting the appropriate weight calculation method plays a decisive role in the rationality of the evaluation. The existing weight determination methods include subjective weighting methods such as the expert scoring method [51], analytic hierarchy process (AHP) [52], and objective weighting methods, such as the entropy method, the principal component analysis method [53], and the coefficient of variation method [54]. In addition, there are subjective and objective comprehensive integration weighting methods [55].

In the process of multi-level decision making, the AHP is widely applicable. The core use of the AHP is to solve multi-objective decision-making problems by constructing a hierarchical structure model and using operational research methods. The complex problems are refined layer by layer to form a systematic and multi-criteria structure, and then the weights of each factor are calculated by mathematical methods (Figure 9). The specific steps include (1) establishing a hierarchical structure model; (2) establishing a judgment matrix and solving the weight vector by comparing with each other; (3) a single-layer arrangement and consistency test; (4) an overall level arrangement and consistency test; and (5) calculating the weight results and making decisions. This method is widely used in project risk management and multi-factor evaluation of complex systems [56], which provides effective support for scientific decision making in engineering construction. In recent years, domestic and foreign scholars have widely applied the AHP to the study of urban underground space suitability. Sterling et al. conducted a multi-factor comprehensive evaluation of the suitability of underground space in Minneapolis, United States, combined with geological conditions [57]. However, the analytic hierarchy process, as a subjective weighting method, does not make full use of data characteristics and may have an impact on the accuracy of the evaluation results [58].

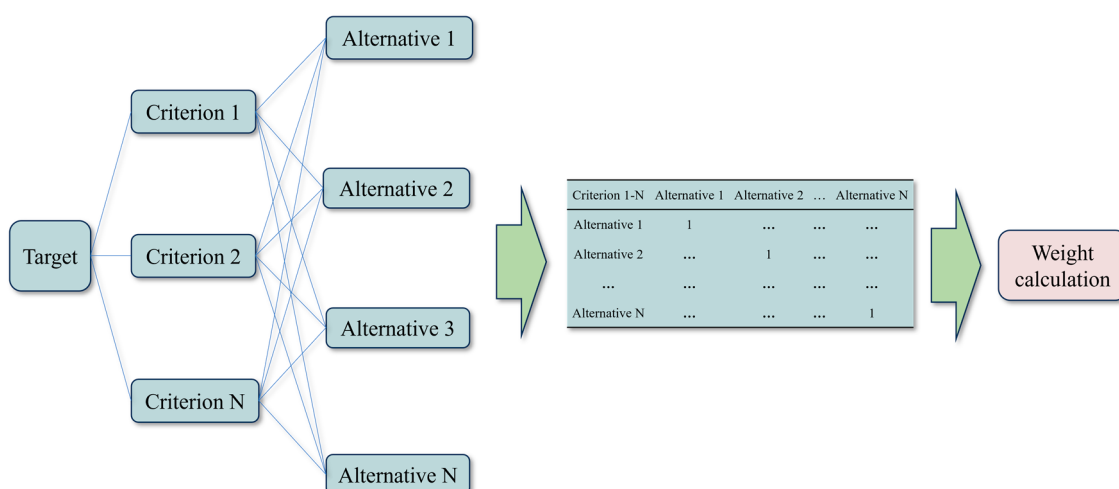


Figure 9. AHP method flowchart.

The entropy weight rule is based on the discreteness of the data to determine the weight, eliminating the impact of subjective factors. In combination with GIS technology, Yalcin et al. used the entropy method to carry out geothermal field exploration to explore new geothermal resources [59]. Although the entropy weight method can reduce subjective errors, sometimes it may ignore the importance of factors, resulting in secondary factors being given higher weights. The subjective weighting method is simple in calculation, but it is easily affected by human experience and has great uncertainty. In order to overcome the limitations of the AHP and entropy weight method in practical application, in recent years, the combination weighting method has effectively combined the entropy weight method with the AHP. Zhou et al. used the combination weighting method of the entropy weight method and the AHP to comprehensively determine the weight coefficient of each index (Table 2) [60]. According to the confidence criterion, the rockburst risk assessment of the Sangzhuling Tunnel in the Sichuan–Tibet traffic corridor was carried out, and good prediction results were obtained. The combination weight method based on gray correlation analysis determines the weight level by calculating the similarity between the continuous sequence and the reference sequence, which makes the evaluation more objective and applicable [61].

Table 2. The weight of each evaluation index of the Sangzhuling Tunnel in China [60].

Evaluating Indicator	σ_c/σ_{max}	σ_θ/σ_c	σ_c/σ_t	K_v	W_{et}
Subjective weights	0.205	0.205	0.065	0.328	0.197
Objective weights	0.117	0.267	0.040	0.364	0.212
Combination weight	0.164	0.233	0.054	0.345	0.204

Note: σ_c (uniaxial compressive strength of rock). σ_{max} (maximum principal stress on the tunnel wall). σ_θ (maximum tangential stress on the tunnel wall). σ_t (uniaxial tensile strength of rock) K_v (Rock Mass Integrity Index). W_{et} (Rock Elasticity Index).

In addition, relevant disciplines have also introduced genetic algorithms, which show good prospects in the applicability and efficiency of combination weighting [62]. In recent years, mathematical models such as fuzzy mathematics, neural networks, and cloud models have been widely used in three-dimensional engineering geological comprehensive evaluation. The fuzzy comprehensive evaluation method combines the membership degree theory and the AHP in fuzzy mathematics, transforming qualitative evaluation into quantitative analysis, and it is an important tool for engineering geological evaluation. The neural network model consists of an input layer, a hidden layer, and an output layer. Each layer transmits information through a weight connection (Figure 10). In engineering geological evaluation, neural networks can effectively deal with nonlinear and complex data relations. By learning a large number of geological data, they can automatically identify the relationship between different geological characteristics to realize the comprehensive evaluation of engineering geology.

Durmisevic et al. evaluated the quality of underground space based on neural networks [63]. Through the quantitative treatment of fuzziness and uncertainty, the cloud model uses MATLAB (MathWorks, Natick, MA, USA, <https://www.mathworks.com/products/matlab.html>, accessed on 1 February 2025) programming to generate the normal cloud map of the key indicators at each level (Figure 11) to calculate the cloud correlation degree of each construction site at different stability levels. This method has been widely used in the field of underground space suitability assessment, slope stability, and tunnel stability analysis.

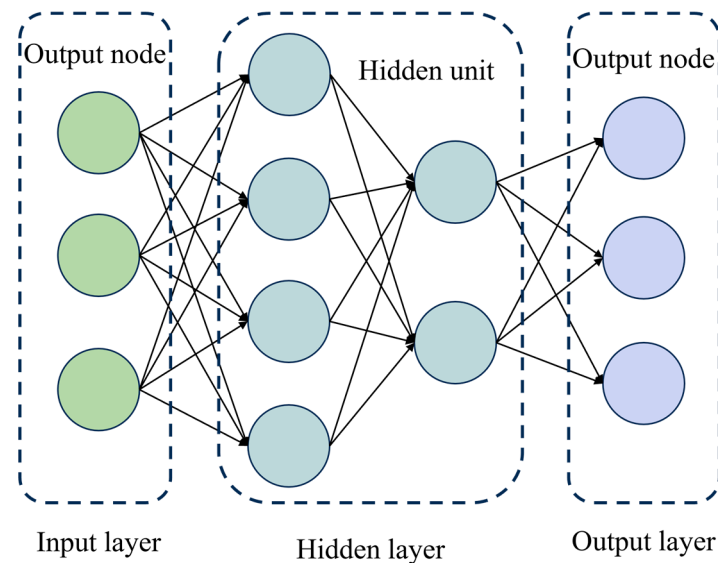


Figure 10. The principle of the artificial neural network.

This method has been widely applied in the fields of underground space suitability evaluation, slope stability analysis, and tunnel stability research. For example, Tan et al. used a combination of a finite interval cloud model and a genetic algorithm for weighted aggregation to evaluate the suitability of urban underground space in Wuhan Changjiang New Town [64]. Lin et al. applied an improved normal cloud model in combination with fuzzy random theory to quantitatively assess the construction risk of the Tiger Mountain Tunnel cross-section [65]. Shen et al. proposed a cloud model-based seismic assessment method for tunnels, integrating multiple damage indicators to significantly enhance the accuracy and reliability of the evaluation [66]. Additionally, Yan et al. introduced a hybrid AHP-NFR (Normalized Frequency Ratio) CM (cloud model) evaluation method for landslide susceptibility analysis, effectively addressing the issues of randomness and fuzziness [67]. Zhang et al. developed a new health evaluation model for shield tunnel linings based on combination weighting and finite interval cloud models, providing new insights into the health monitoring of shield tunnels [68].

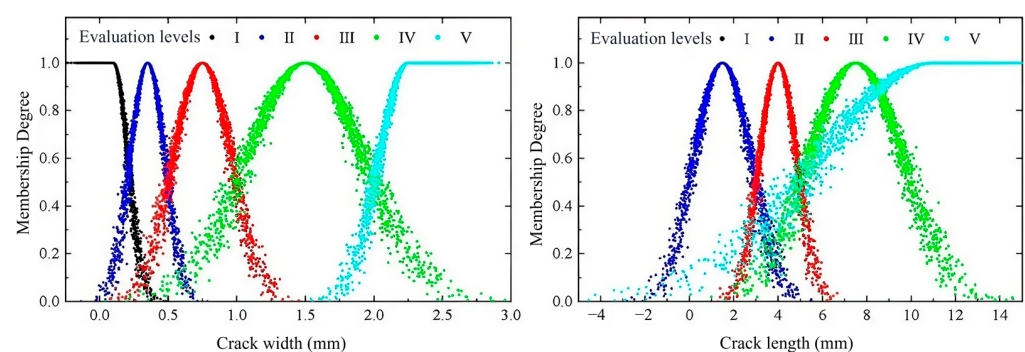


Figure 11. Cloud model diagram of the health evaluation index of shield tunnel lining [69].

2.4. Construction of the Three-Dimensional Engineering Geological Evaluation Model

Through the analysis of the three-dimensional engineering geological evaluation index data set and using the appropriate evaluation method, the weight of each three-dimensional engineering geological index is calculated to obtain the final comprehensive evaluation score. On this basis, the results of the comprehensive evaluation are organically coupled with the data of a three-dimensional geological model, which breaks the limitations of

traditional two-dimensional evaluation and forms a more comprehensive, accurate, and dynamic three-dimensional engineering geological evaluation model (Figure 12).

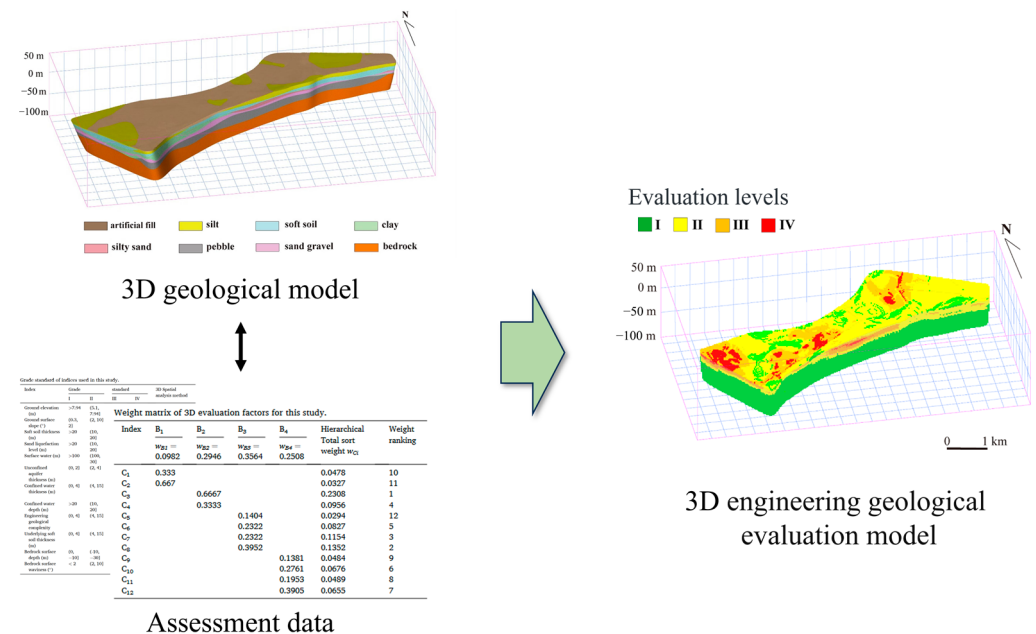


Figure 12. The construction process of the 3D (three-dimensional) engineering geological evaluation model. (Figure is modified from [9].).

With the help of visualization technology, the three-dimensional engineering geological evaluation model presents complex geological data and evaluation results intuitively, which greatly improves the risk assessment and decision-making efficiency of engineering projects in complex geological environments. Through the comprehensive evaluation and accurate modeling of geological resources, the three-dimensional engineering geological evaluation model can support the rational allocation of resources and promote the coordinated development of engineering and environment. Through this integrated technical means, the three-dimensional engineering geological evaluation model can not only improve the safety and economic benefits of the project but also provide a scientific basis for environmental protection, resource conservation, and ecological restoration and promote the development of the engineering geological field in a more sustainable direction.

3. Results

The three-dimensional engineering geological evaluation model constructs a powerful visual analysis platform by integrating multiple data sources, which provides strong support for the comprehensive analysis of engineering projects. On this basis, the model conducts an in-depth evaluation of key engineering geological parameters, providing a scientific decision-making foundation for engineering planning and design. It helps optimize resource allocation and enhances the safety, feasibility, and sustainability of the engineering project. The model can not only accurately predict potential risks under complex geological conditions but also be applied to the development and sustainable utilization of resources. Through systematic analysis and evaluation, it effectively promotes the rational use of resources and ensures the long-term stability and sustainable development of the project.

Three-dimensional engineering geological evaluation modeling has been widely used in urban engineering geological evaluation, especially in the development and utilization of urban underground space. The effective use of urban underground space depends on the planning of the system, and this planning is inseparable from the in-depth suitability evaluation of the underground space in the study area. Through scientific suitability

evaluation, the potential value and availability of underground space and its relationship with the surrounding environment can be comprehensively evaluated. This process not only helps to identify and optimize resource allocation but also effectively avoids potential engineering risks and environmental impacts, ensuring safety, environmental sustainability, and economic feasibility [69]. The geological environment conditions that affect the utilization of underground space are highly interrelated and constitute a complex system.

To this end, Price et al. combined the three-dimensional geological model with the two-dimensional geospatial data of the urban underground space index (UUS) and analyzed its impact on sustainable development and energy goals by evaluating the underground space index of the Earls Court area in London, England [11]. Dou et al. proposed a new UUS geological suitability evaluation framework and carried out a three-dimensional evaluation analysis in Qianjiang New Town, Hangzhou, which verified the reliability of the framework [9]. The framework effectively integrates two-dimensional and three-dimensional geological information and provides more reasonable and rich evaluation results, thus promoting the scientific planning and sustainable use of urban underground space. Deng et al. proposed a framework for engineering geological suitability evaluation based on three-dimensional geological modeling and an AHP cloud model, aiming to comprehensively evaluate the geological suitability of underground space in the Sanlongwan area, Foshan City, Guangdong Province [70]. Through systematic analysis, the framework predicts the difficulty of underground space excavation in the study area and provides a scientific basis for the development of regional underground space. Pu et al. proposed a spatial variable weight assignment method based on order relation analysis, the entropy weight method, improved gray relational analysis (GRA), and the spatial weight adjustment coefficient and developed a three-dimensional urban underground space evaluation method based on the three-dimensional geological model and spatial variable weight [71]. These studies show that three-dimensional engineering geological evaluation modeling plays a key role in the development of urban underground space and can provide reliable decision support for policymakers and engineering practitioners. Through the comprehensive analysis of underground space, the three-dimensional engineering geological evaluation model can accurately predict the changes in geological conditions and then effectively reduce the potential risks in the process of project implementation.

In the field of geological disaster prevention, three-dimensional engineering geological evaluation modeling has been widely applied in various industries, such as transportation and water conservancy, especially in the stability assessment of slopes, tunnels, and underground plants, achieving significant progress. Jia et al. constructed a three-dimensional deterministic model, combining Monte Carlo simulation and a GIS-based three-dimensional limit equilibrium model [72]. They successfully identified the critical slip surface and calculated the corresponding safety factor, providing an accurate evaluation of shallow landslide hazards. Palazzolo et al. used SCOOPS 3D to establish a three-dimensional slope prediction model and applied a genetic algorithm for multi-objective optimization to calibrate geological parameters, effectively improving the accuracy of landslide predictions [73]. Dai et al. proposed a dynamic evaluation method for landslide susceptibility during the reservoir impoundment process, combining a three-dimensional geological evaluation model with InSAR displacement data, successfully evaluating landslide susceptibility before and after the impoundment of the Baihetan Dam [74]. By assessing the pollution levels of groundwater at various depths, they provided important theoretical and practical guidance for site remediation and the sustainability of resource utilization. Ugenti et al. constructed a three-dimensional geological model at the urban regional scale, performing a three-dimensional limit equilibrium analysis, and they identified areas prone to landslides, offering key support for geological disaster risk management [75]. In the assessment of surrounding rock for tunnels and underground plants, Zhang et al. used an improved

coupled Markov chain model to quantitatively evaluate the impact of geological uncertainty and soil spatial variability on tunnels [76]. They also employed Kendall's correlation coefficient to assess the model, highlighting the necessity of considering geological uncertainties. Sun et al. developed a fuzzy comprehensive evaluation model, which, combined with the evolution trend of MS event center frequency, quantitatively described the early warning status of surrounding rock instability [77]. Through this model, they successfully achieved a visual assessment of the potential damage area and degree of surrounding rock in the underground power plant of the Shuangjiangkou hydropower station, providing an effective evaluation method for the stability analysis of surrounding rock in underground engineering projects.

In the field of resource and energy development, Fegh et al. utilized artificial neural networks to predict permeability, and based on this, they constructed a three-dimensional reservoir model, achieving a comprehensive quantitative characterization of carbonate oil and gas reservoirs [78]. Thanh et al. proposed a three-dimensional CO₂ integrated reservoir geological evaluation model based on artificial neural networks and assessed the CO₂ sequestration capacity of fractured reservoirs in the Cuu Long Basin of Vietnam [79]. Akinwumiju et al. conducted three-dimensional geological statistical modeling of the distribution of key geochemical, rock physics, and geomechanical properties to evaluate the potential for residual shale gas extraction in geological structures [80]. Guo et al. proposed a comprehensive evaluation model of natural gas hydrate reservoir brittleness based on gray relational analysis [81]. By integrating the hydraulic fracturing experimental results from natural gas hydrate sediments, they assessed the brittleness of hydrate reservoirs and developed a three-dimensional brittleness construction condition identification diagram, achieving a fast and accurate evaluation of hydrate reservoirs. Zou et al. constructed a high-resolution three-dimensional model and, by combining multiple tidal energy evaluation indicators, such as energy flux density and resource reserves, performed a systematic quantification and spatial distribution analysis of resource reserves, thereby achieving a comprehensive evaluation of tidal stream energy resources [82]. Chang et al. established a three-dimensional visualization evaluation model based on geophysical measurements and logging data and completed the quantitative assessment of the Qing Shui geothermal reservoir [83]. Blannin et al. developed a three-dimensional resource evaluation model based on geographical information statistics to assess the resource potential of tailings storage [84]. In summary, three-dimensional engineering geological evaluation models play a significant role in resource development and utilization, providing reliable support for the efficient and safe extraction of energy.

4. Discussion

Currently, the three-dimensional engineering geological evaluation model faces two main issues: insufficient accuracy and a lack of numerical simulation validation. Existing three-dimensional geological evaluation models often fail to fully consider key factors, such as the uncertainty of geotechnical engineering parameters and surface and underground structures, resulting in a gap between the value of the constructed model and its expected goals in practical applications. Furthermore, three-dimensional geological evaluation models and numerical simulations are often independent of each other, lacking simulation results based on actual data to verify the reliability and accuracy of the models, which limits their practical application potential and value.

In order to solve this problem, it is suggested to use the Bayesian inference method to update and optimize the posterior distribution of rock mass parameters, which can significantly improve the accuracy of the model. Furthermore, combined with the geological characteristics of different scales, precision levels, and local areas, a more refined

three-dimensional engineering geological evaluation model is established according to the needs and data density of specific engineering projects (Figure 13). In addition, different engineering geological models will lead to different deformation characteristics and failure modes [85]. Therefore, with the help of geological data, the establishment of a three-dimensional engineering geological evaluation model and the prediction of its deformation and failure modes will help to improve the prediction ability of the model and the safety of the project. To ensure that the constructed three-dimensional engineering geological evaluation model has high accuracy and practicability, it is recommended to integrate numerical simulation technology into model analysis. Through the numerical simulation method, different geological conditions can be simulated to simulate deformation, stress distribution, and potential failure mode and further verify the reliability of the three-dimensional engineering geological evaluation model. In the practical application process, by comparing and analyzing the actual monitoring data, the model parameters can be adjusted and optimized to improve its prediction ability and accuracy.

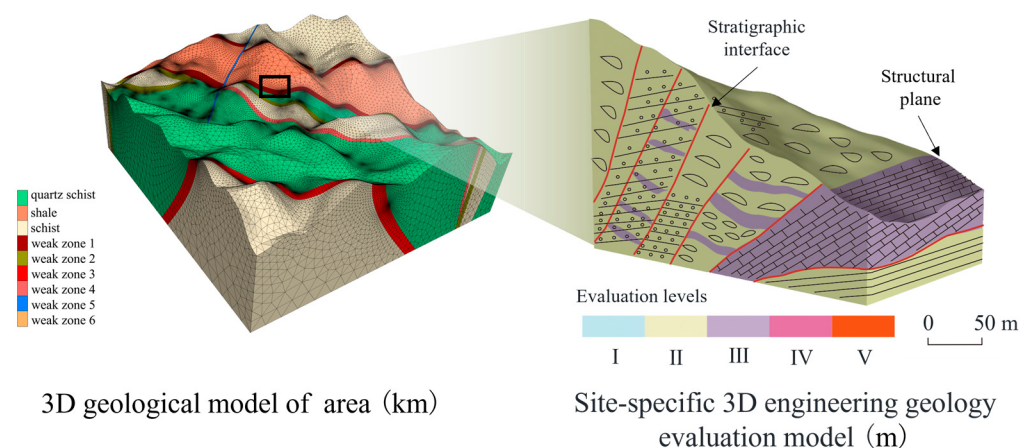


Figure 13. Three-dimensional evaluation modeling examples of different scales.

The three-dimensional engineering geological evaluation model has enormous potential in the fields of resource assessment and disaster analysis. In the future, by integrating cutting-edge technologies, such as big data analysis, high-performance computing, artificial neural networks, and artificial intelligence, we aim to establish an intelligent database that combines disaster analysis and resource evaluation [43]. This will enable the intelligent extraction and analysis of geological data and the automatic generation of three-dimensional engineering geological evaluation models. This approach not only enhances the reliability of three-dimensional geological evaluation modeling but also provides more accurate decision support for geological disaster assessment and resource management, promoting high-quality and sustainable development of the geological environment.

5. Conclusions

This paper systematically combines the construction method and process of the three-dimensional engineering geological evaluation model. The three-dimensional engineering geological evaluation model significantly improves the model's applicability by organically coupling the engineering geological evaluation results with the three-dimensional geological model. Three-dimensional geological modeling methods mainly include explicit and implicit modeling, both of which have advantages and disadvantages. In practical engineering, we usually choose to combine these two methods and adopt the method of multi-source data fusion to give full play to their respective advantages. The application of the probabilistic model and dynamic three-dimensional geological model effectively solves the problem of geological uncertainty.

Compared with the traditional two-dimensional evaluation system, the three-dimensional evaluation system has obvious advantages, especially in the comprehensive consideration of various influencing factors. The selection of evaluation indexes should follow the principles of systematicness, hierarchy, scientificity, and practicability. Selecting the appropriate evaluation index of engineering geological space and adopting the scientific quantification and classification method can provide an effective evaluation basis for the construction design of the project. The subjective evaluation method and the objective evaluation method have their limitations, and the combination weighting method effectively improves the accuracy and applicability of the evaluation results by combining the advantages of the two. In addition, applying neural networks and cloud models offers innovative approaches for engineering geological evaluation.

The three-dimensional engineering geological evaluation model not only enables accurate prediction of geological disaster risks under complex geological conditions but also has applications in resource development and sustainable utilization. However, existing three-dimensional engineering geological evaluation models still face issues, such as insufficient accuracy and lack of numerical simulation validation, when dealing with complex geological conditions. To address these problems, it is recommended to apply cutting-edge technologies, such as big data analysis and machine learning, to establish multi-scale three-dimensional engineering geological evaluation models and further validate the model's reliability through numerical simulation methods. In the future, the application of advanced technologies, such as artificial neural networks and artificial intelligence, will provide new opportunities for the development of three-dimensional engineering geological evaluation models.

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