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Research on Geological Safety Evaluation Index Systems and Methods for Assessing Underground Space in Coastal Bedrock Cities Based on a Back-Propagation Neural Network Comprehensive Evaluation–Analytic Hierarchy Process (BPCE-AHP)

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Abstract: With the rapid development of the economy in China, the scale and quantity of urban underground space development continue to grow rapidly; as such, geological safety problems in urban underground space development and utilization are a research hotspot at present. Therefore, it is important to establish a high-quality evaluation index system and method for assessing the geological safety of urban underground spaces in coastal bedrock. Taking the typical area of Qingdao as an example, this study establishes an effective system for evaluating the geological safety of urban underground space according to the geological background, hydrogeology, engineering geology, and unfavorable geological phenomena in the Hongdao Economic Zone of Qingdao. Then, the method of evaluating the geological safety of urban underground space was studied. Through a comprehensive analysis and comparison of the fuzzy comprehensive evaluation–analytic hierarchy process (FCE-AHP), the grey relation comprehensive evaluation–analytic hierarchy process (GRCE-AHP), the matter-element comprehensive evaluation–analytic hierarchy process (MECE-AHP), and the back-propagation neural network comprehensive evaluation–analytic hierarchy process (BPCE-AHP), it was determined that the back-propagation neural network comprehensive evaluation–analytic hierarchy process (BPCE-AHP) was an ideal method for evaluating the geological safety of underground space in Qingdao's coastal bedrock area. This method was used to evaluate the geological safety of the study area, and the evaluation results were verified; this further proved the practicability and rationality of the back-propagation neural network comprehensive evaluation–analytic hierarchy process (BPCE-AHP).

Keywords: coastal bedrock city; underground space; geological safety evaluation; BPCE-AHP

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1. Introduction

For some time, geologists in developed countries have been paying increasing attention to the geological environment of urban underground space. Scientists increasingly recognize the importance of regional geological environment safety assessments in the process of urban construction planning and the foresight such assessments provide; researchers have gradually developed a scientific, mature, and systematic planning system [1–5]. In 1994, Maurenbrecher et al. analyzed the suitability of tunnel construction in Amsterdam, The Netherlands [6]. In 1995, American geologists established a geological disaster risk assessment system for the Glenwood Springs area [7]. In 1998, Ronka et al. established an evaluation model for the suitability of the development and utilization of underground space resources in the rock stratum area [8]; moreover, Dyad'kin, Yu D. emphasized that the efficient development of underground space must involve a consideration of the related environmental and geotechnical problems [9]. In 2003, Umnov, V. A. et al., advanced a geological environment assessment method for the development and utilization of underground space [10]. In 2007, American geologist De Rienzo, F. proposed a 3D geological underground structure model based on GIS [11]. In 2012, researchers from the United States and Japan began to evaluate the geological environment that affects the development of deep and multi-level underground space [12].

In recent years, more and more attention has been paid to the development and utilization of urban underground space in China. In 2005, Tong proposed the development path of urban underground space in China [13]. Then, in 2006, Ding et al. evaluated the risks related to the urban geological environment in Southwest China at the district level [14]. In 2008, Liang et al. conducted a systematic and detailed study on the theory, methods, and application of geological environment assessment results [15]. In 2013, Wang et al. analyzed the factors affecting the development potential of urban underground space [16]. In 2020, Zhao et al. established an original suitability classification system for underground space in coastal bedrock cities [17]. Also in 2020, Dong et al. studied the methods and contents of geological safety evaluations of urban underground space [18]. In 2021, a three-tiered comprehensive green hydropower evaluation index system was constructed and an improved matter-element extension model was established [19]. In 2021, Hao et al. proposed a quantitative spatial geohazard assessment model for railway alignment optimization. Then, this model was incorporated into a previously developed cost–hazard alignment optimization model [20].

Currently, there is no systematic geological safety evaluation method that is suitable for assessing underground space in coastal bedrock cities in the Qingdao area. Therefore, the purpose of this paper is to propose an evaluation index system, establish a mathematical model, and develop a new method for evaluating the geological characteristics of the Qingdao area. Accounting for the geological background, hydrogeology, engineering geology, and unfavorable geological phenomena in Qingdao, we study methods for the evaluation of geological safety. Finally, we use data from Metro Line 2 to verify our method.

2. Regional Geology

2.1. Structure and Stratigraphy

In terms of its tectonic position, the study area is located at the junction of North China plate and two Class I tectonic units of the Qinling–Dabie–Sulu orogenic belt. The northwest belongs to the Jiaoliao uplift area of the North China plate (II), and the southeast belongs to the Jiaonanweihai uplift area of the Qinling–Dabie–Sulu orogenic belt (II); this belt spans three Class III tectonic units, namely, the Jiaobei uplift, the Jiaolai basin, and the Jiaonan uplift, covering several Class IV and V tectonic units (Figure 1).

Qingdao is located at the junction of the North China plate and two first-class tectonic units of the Qinling–Dabie–Sulu orogenic belt. It has undergone a long-term geological evolution and transformation of deep and large faults, resulting in complex tectonic forms and obvious differences in various tectonic features in different geological tectonic units.

Mesozoic Cretaceous intrusive strata are developed in the study area, with typical coastal bedrock that is dominated by magmatic rocks; the Mesozoic magmatic rocks are the most developed. It includes widely distributed typical granite, some magmatic rocks such as andesite and basalt, and a small number of clastic rocks, such as volcanic breccia and tuff.

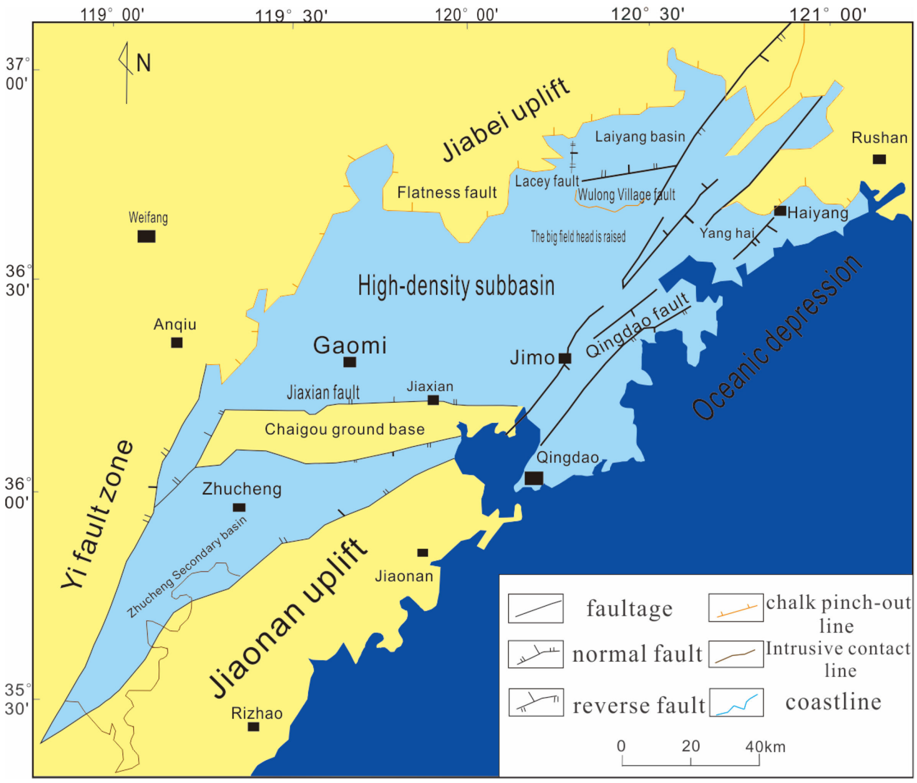


Figure 1. Sketch map of geological structure of Qingdao and its surrounding areas (Modified from reference [17]).

2.2. Hydrogeological Conditions

The Qingdao area is in a hydrogeological region with loose rocks, clastic rocks, and metamorphic rocks in the low mountains and hills of eastern Shandong Province. The Jiaolai depression is the main hydrogeological subarea and the Jiaonan and Jiaobei uplifts are the southern slope's hydrogeological subareas.

2.3. Engineering Geological Conditions

The engineering geological conditions of Qingdao are directly influenced and controlled by topography, geomorphology, stratum lithology, geological structure, hydrogeological conditions, internal and external dynamic geological processes, and human activities. The engineering geology of the rock and soil in Qingdao can be divided into two types: the rock engineering geology type and the soil engineering geology type.

2.4. Adverse Geological Processes

Adverse geological action has a significant influence on the safety of underground engineering and can even directly damage underground engineering. The adverse geological processes in the study area are mainly caused by natural and human factors, which have an impact on the safety of underground space development; they include earthquakes, active faults and ground fissures, collapses, landslides, surface subsidence, sand liquefaction, slope instability, seawater intrusion, and so on.

3. Establish a Geological Safety Evaluation Index System

The geological environment of underground space in coastal cities constitutes a complex multi-level and multi-factor system. The geological factors affecting the development and utilization of underground space have complex and changeable characteristics. At present, there is no unified system for evaluating geological safety. According to the geology, hydrogeology, engineering geology, and unfavorable geological process of the study area, scientific and reasonable principles should be followed when selecting safety evaluation indexes. The hierarchy, diversity, fuzziness, and uncertainty of the evaluation index system should be comprehensively considered to truly reflect the safety characteristics of underground space development and utilization in different study areas; additionally, clear concepts and calculation methods should be provided to ensure the rationality and scientificity of the evaluation process and results.

Based on these guiding principles, when selecting evaluation indicators, we should consider overall characteristics and all-round influencing factors. There is the characteristic of independence, and there is no redundant information interference. It also has the characteristics of operability and is convenient for complete treatment; finally, it should conform to uniform standards as much as possible. Therefore, according to geological environment safety, there are six major influencing factors. Thus, the index system for evaluating the geological safety of urban underground space is established (Figure 2, Table 1). It comprises the following layers.

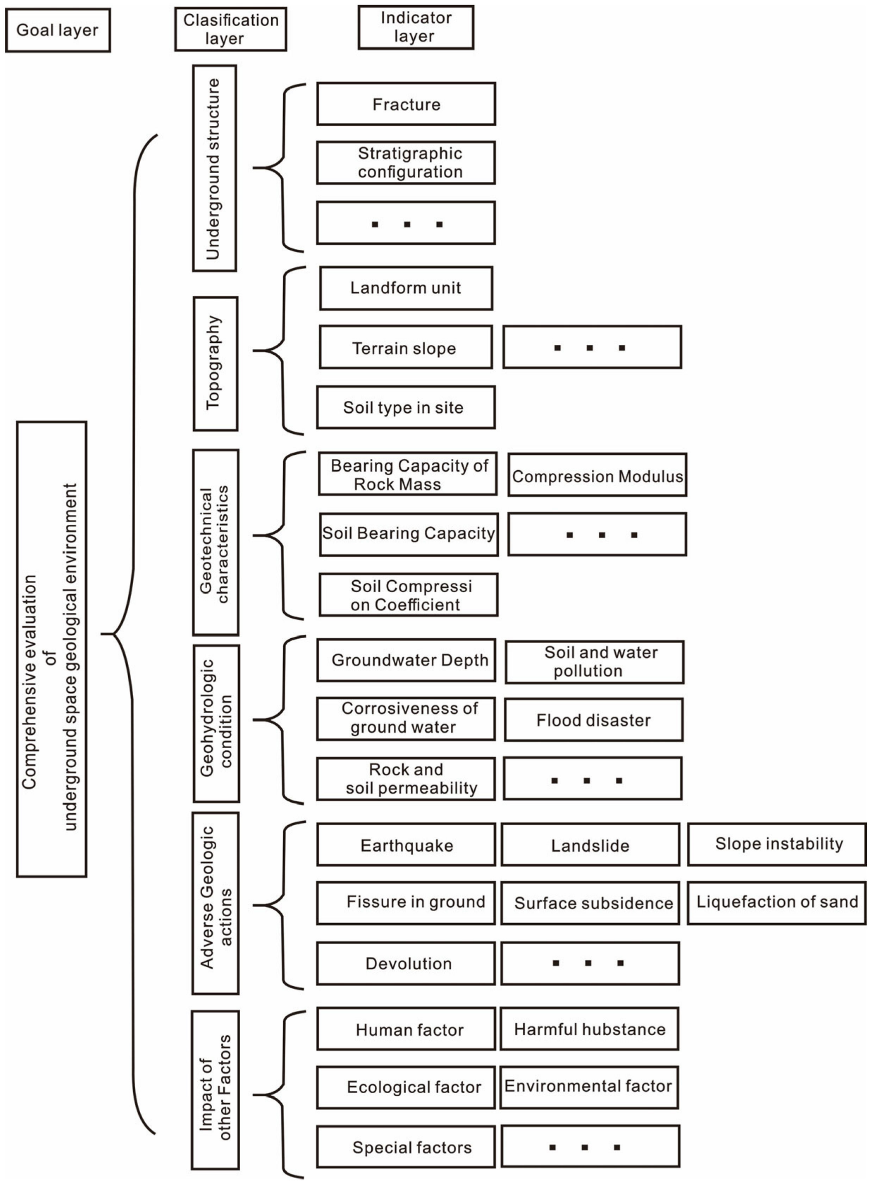


Figure 2. Comprehensive evaluation index system for geological safety of urban underground space development.

Table 1. Index system and classification of underground space geological safety evaluation in Qingdao Hongdao Economic Zone.

Indicator \ Grade	1	2	Data Sources
Geological Safety of urban underground space (A)	Underground structure (B1)	Lateral active fault combination (C1)	14 regional geological survey reports, 225 boreholes of urban geological survey project
		Stereo structure of rock soil mass (C2)	670 field investigation and investigation reports
	Topography (B2)	Landform unit (C3)	14 regional geological survey reports
		Terrain slope (C4)	14 regional geological survey reports
		Soil type in site (C5)	290 geotechnical engineering detailed investigation reports and experimental test analysis
	Geotechnical characteristics (B3)	Bearing capacity of rock mass (C6)	290 geotechnical engineering detailed investigation reports and experimental test analysis
		Soil bearing capacity (C7)	290 geotechnical engineering detailed investigation reports and experimental test analysis
		Compression modulus (C8)	290 geotechnical engineering detailed investigation reports and experimental test analysis
	Geohydrologic condition (B4)	Groundwater level (C9)	59 hydrogeological boreholes and collection data
		Sea water intrusion (C10)	59 hydrogeological boreholes and collection data
		Permeability (C11)	Test analysis and collection data
		Flood disaster (C12)	Field investigation and collection data
	Adverse geologic action (B5)	Earthquake disaster (C13)	collection data
		Earth deformation (C14)	290 geotechnical engineering detailed investigation reports and experimental test analysis
		Liquefaction of sand (C15)	Geotechnical engineering investigation report and field investigation
		Fissure in ground (C16)	190 engineering geological boreholes and field investigation

First, the target layer, which indicates the purpose of solving the problem, that is, to evaluate the geological safety of urban underground space.

Second, the classification layer, which indicates the types of factors affecting the overall goal. At present, the scheme recognized by most scholars is that the geological safety evaluation of urban underground space can be divided into six categories: the underground space structure, topography, rock and soil characteristics, hydrogeological conditions, adverse geological effects, and other influencing factors.

Third, the index layer, representing the same type of influencing factors. For example, the characteristics of rock and soil include the rock bearing capacity, the soil bearing capacity, soil compressibility, and other indicators.

According to the requirements of practical applications, a more complete index system can be established. For example, the characteristic index layer of rock and soil mass can add the deformation modulus of other rock and soil masses, and the water environment condition index layer can add groundwater erosion, water and soil pollution, etc. An adverse geological action index layer can be added, including slope instability, collapsed landslides, shore erosion, river erosion, etc. In addition, some human, ecological, and environmental factors can be added.

However, in the actual safety evaluation, the selection of evaluation indicators should be combined with evaluation experience and regional geological features to select a clear indicator system.

4. Constructing a Geological Safety Evaluation Method

Based the different kinds of methods used in previous evaluations, this study randomly generated many objective sample data, according to the index system, to carry out numerical simulation calculation tests for various index weight assignment methods and comprehensive evaluation methods. The multi-theory integrated neural network evaluation method was used to integrate various uncertainty theories and to absorb the characteristics and advantages of various comprehensive evaluation methods; finally, it was integrated into a neural network to form a comprehensive evaluation method with stronger applicability and higher evaluation quality than other methods.

4.1. Establishment of a Mathematical Model

Combined with coastal mountain landforms, seawater erosion, earthquakes, floods, landslides, soft soil liquefaction, and other geological environment problems, an evaluation index system suitable for the actual geological conditions of the study area is established.

Because the extraction and membership degree of each primary factor is a fuzzy concept and a fuzzy judgment process, in order to facilitate analysis and quantification, a numerical quantification criterion is established (Table 2).

Table 2. Quantitative criteria for influencing factors of geological safety evaluation of underground space in coastal cities.

Influencing Factors of Underground Space Development	Quantitative Method of Influencing Factors	Data Sources
Lateral active fault combination	The distribution of active fault area assignment	14 regional geological survey reports, 290 geotechnical engineering survey reports, 225 engineering geological boreholes
Stereo structure of rock soil mass	Geotechnical stratum combination type assignment	670 field investigation and investiga-tion reports
Landform unit	River terrace series assignment	14 regional geological survey reports and data collection
Terrain slope	Calculate slope with terrain contour line	14 regional geological survey reports and topographic maps collection
Soil type in site	Regional rock and soil and special rock and soil distribution assignment	290 geotechnical engineering investigation reports and field investigation
Bearing capacity of rock mass	Digitalization of bearing capacity of rock and soil mass	Experimental test analysis and 290 geotechnical engineering investigation reports
Soil bearing capacity	Digitalization of bearing capacity of rock and soil mass	Experimental test analysis and 290 geotechnical engineering investigation reports
Compression modulus	Digitalization of the compression modulus of soil	Experimental test analysis and 290 geotechnical engineering investigation reports
Treatments of waste water	Surface water impact degree assignment	59 hydrogeological boreholes, 290 water quality test analysis and survey reports
Groundwater level	Digitalization of groundwater depth	59 hydrogeological boreholes, 290 water quality test analysis and survey reports
Depth of confined water	Digitalization of confined water depth	59 hydrogeological boreholes, 290 water quality test analysis and survey reports
Groundwater depth	Digitalization of diving depth	59 hydrogeological boreholes, 290 water quality test analysis and survey reports
Groundwater corrosion	Groundwater corrosion degree assignment	59 hydrogeological boreholes, 290 water quality test analysis and survey reports
Sea water encroachment	Seawater erosion degree assignment	59 hydrogeological boreholes, 290 water quality test analysis and survey reports
Permeability	Digitalization of permeability coefficient	59 hydrogeological boreholes, 290 water quality test analysis and survey reports

Table 2. *Cont.*

Influencing Factors of Underground Space Development	Quantitative Method of Influencing Factors	Data Sources
Flood disaster	River erosion and flood inundation capacity assignment	14 regional geological survey reports, 290 geotechnical engineering survey reports, 225 engineering geological boreholes, 59 hydrogeological boreholes
Earthquake disaster	Earthquake damage degree assignment	14 regional geological survey reports, 290 geotechnical engineering survey reports, 225 engineering geological boreholes, 59 hydrogeological boreholes
Land subsidence	Land subsidence intensity and trend assignment	14 regional geological survey reports, 290 geotechnical engineering survey reports, 225 engineering geological boreholes, 59 hydrogeological boreholes
Landslide collapse	Landslide collapse degree assignment	14 regional geological survey reports, 290 geotechnical engineering survey reports, 225 engineering geological boreholes, 59 hydrogeological boreholes
Liquefaction of sand	Sand liquefaction distribution assignment	14 regional geological survey reports, 290 geotechnical engineering survey reports, 225 engineering geological boreholes, 59 hydrogeological boreholes
Fissure in ground	Ground fissure distribution assignment	14 regional geological survey reports, 290 geotechnical engineering survey reports, 225 engineering geological boreholes, 59 hydrogeological boreholes
Engineering construction	Engineering construction influence degree assignment	14 regional geological survey reports, 290 geotechnical engineering survey reports, 225 engineering geological boreholes, 59 hydrogeological boreholes
Contamination	Pollution impact degree assignment	14 regional geological survey reports, 290 geotechnical engineering survey reports, 225 engineering geological boreholes, 59 hydrogeological boreholes
Energy exploitation	Energy mining impact degree assignment	14 regional geological survey reports, 290 geotechnical engineering survey reports, 225 engineering geological boreholes, 59 hydrogeological boreholes

According to the principle of the AHP algorithm, the judgment matrix of each level of factors is established (Tables 3–8), and the consistency test is carried out. Finally, the factor weight of the underground space geological safety evaluation index in Hongdao District of Qingdao is determined (Table 9).

Table 3. A–B judgment matrix and index relative weight.

A–B	B_1	B_2	B_3	B_4	B_5	Index Relative Weight
B_1	1	5	3	1	1	0.3114
B_2	1/5	1	1/3	1/3	1/2	0.0737
B_3	1/3	3	1	1	1	0.1812
B_4	1	3	1	1	1	0.2257
B_5	1	2	1	1	1	0.2081

Table 4. B_1–C judgment matrix and index relative weight.

B_1–C	C_1	C_2	Index Relative Weight
C_1	1	1/5	0.1667
C_2	5	1	0.8333

Table 5. B_2–C judgment matrix and index relative weight.

B_2–C	C_3	C_4	C_5	Index Relative Weight
C_3	1	2	1/3	0.2297
C_4	1/2	1	1/5	0.1220
C_5	3	5	1	0.6483

Table 6. B_3–C judgment matrix and index relative weight.

B_3–C	C_6	C_7	C_8	Index Relative Weight
C_6	1	1	1	0.3333
C_7	1	1	1	0.3333
C_8	1	1	1	0.3333

Table 7. B_4–C judgment matrix and index relative weight.

B_4–C	C_9	C_{10}	C_{11}	C_{12}	Index Relative Weight
C_9	1	5	1	1/3	0.3125
C_{10}	1/5	1	1/5	1/5	0.0625
C_{11}	1	5	1	1	0.3125
C_{12}	1	5	1	1	0.3125

Table 8. B_5–C judgment matrix and relative weight.

B_5–C	C_{13}	C_{14}	C_{15}	C_{16}	Index Relative Weight
C_{13}	1	1	1/2	1/2	0.1731
C_{14}	1	1	1	1	0.2448
C_{15}	2	1	1	1	0.2911
C_{16}	2	1	1	1	0.2911

Table 9. Levels of total order, consistency and weight.

Indicator Layer	B1	B2	B3	B4	B5	Index Comprehensive Weight WI	Hierarchical Total Sorting Consistency Test
	W_{B1} = 0.3114	W_{B2} = 0.0737	W_{B3} = 0.1812	W_{B4} = 0.2257	W_{B5} = 0.2081	i = 1, … ,16	
C1	0.1667					0.0519	$CI = \sum_{i=1}^{5} W_{Bi} CI_i = 0.0043$ $RI = \sum_{i=1}^{5} W_{Bi} RI_i = 0.482$ $CR = \frac{CI}{RI} = 0.0089 < 1$
C2	0.8333					0.2595	
C3		0.2297				0.0169	
C4		0.1220				0.0090	
C5		0.6483				0.0478	
C6			0.3333			0.0906	
C7			0.3333			0.0906	
C8			0.3333			0.0906	
C9				0.3125		0.0705	
C10				0.0625		0.0141	
C11				0.3125		0.0705	
C12				0.3125		0.0705	
C13					0.1731	0.0360	
C14					0.2448	0.0509	
C15					0.2911	0.0606	
C16					0.2911	0.0606	

The expression of the comprehensive evaluation model is as follows:

$$\begin{cases} W=[w_1,w_2,\cdots,w_m] & d_g^j=\left\{\sum\limits_{i=1}^{m}\left[w_{jk}(1-r_{ij})\right]^p\right\}^{\frac{1}{p}} \\ R=\begin{pmatrix} R_1 \\ R_2 \\ \cdots \\ R_m \end{pmatrix}\begin{pmatrix} r_{11}r_{12}\ldots r_{1q} \\ r_{21}r_{22}\ldots r_{2q} \\ \cdots\cdots\cdots\cdots \\ r_{m1}r_{m2}\ldots r_{mq} \end{pmatrix} & d_b^j=\left\{\sum\limits_{i=1}^{m}\left[w_{ij}r_{ij}\right]^p\right\}^{\frac{1}{p}} \\ w_{ij}=\frac{w_iS_{ij}(r_{ij})}{\sum\limits_{k=1}^{m}w_kS_{kj}(r_{kj})},(i=1,\cdots m,j=1,\cdots q) & r_j=\frac{1}{1+\left(\frac{d_g^j}{d_b^j}\right)^a} \\ r_j=\frac{r_j}{\sum\limits_{i=1}^{q}r_i},(j=1,\cdots q)|r_j=r_j(q=1) & R_0=[r_1,r_2,\cdots,r_q] \end{cases}$$

In the formula, W is the subsystem indicator weight vector, m is the number of indicators, q is the number of comments, and R is the indicator membership matrix. r_{ij} is the degree of membership of indicator I to comment j, and w_i is the weight of indicator i in the subsystem. w_{ij} is the variable weight function of indicator i for comment j, and S_{ij} (r_{ij}) is the state variable weight function of indicator i for comment j. d_g^j is the min weighted distance of the subsystem belonging to comment j, and d_b^j is the min weighted distance of the subsystem not belonging to comment j. p is the min distance constant, a is the model optimization criterion parameter, and r_j is the comprehensive membership degree of the subsystem to comment j. Finally, R_0 is the normalized comprehensive membership vector of the subsystem.

According to the above equation, there are three parameters to be determined for the comprehensive evaluation model; these are the model optimization criterion parameter a, the min distance constant p, and the state variable weight function S_{ij} (x).

The function of parameter a is to control the speed of function value change. The function of parameter P is to control the degree of influence of the index on comprehensive membership.

When a = 1, p = 1, the comprehensive evaluation model turns into a weighted average model. The expression is

$$r_j=\sum_{i=1}^{m}w_{ij}r_{ij}$$

When a = 2, p = 2, the comprehensive evaluation model is a fuzzy optimization model. The expression is

$$r_j=\frac{\sum_{i=1}^{m}(w_{ij}r_{ij})^2}{\sum_{i=1}^{m}\left[(w_{ij}r_{ij})^2+(w_{ij}(1-r_{ij}))^2\right]}$$

In the evaluation of geological safety, in order to make the evaluation result more reasonable, we usually conceptualize the state variable weight function expression as follows:

$$S(X)=\begin{cases} 1 & x_j\in[0,g],x_j\in[q,1] \\ \frac{1-a}{(g-m)^2}(x_j-m)^2+a & x_j\in(g,m) \\ a & x_j\in[m,n] \\ \frac{1-a}{(n-q)^2}(x_j-n)^2+a & x_j\in(n,q) \end{cases}$$

4.2. Algorithm Selection

The algorithm was developed using MATLAB language. This language is one of the three mathematical software packages with high computational efficiency, complete functions, and easy development. At present, the core algorithms of six commonly used comprehensive evaluation methods have been developed: the entropy weight method, analytic hierarchy process, fuzzy comprehensive evaluation method, grey relational comprehensive analysis method, extension matter-element comprehensive evaluation method, and back-propagation neural network comprehensive evaluation.

Regarding the geological characteristics of the study area, we should consider not only certain factors and information such as structure and quantification in the comprehensive evaluation of geological safety but also a large number of uncertain factors and information, such as unstructured, linguistic, fuzzy, random, grey, and poor data. Therefore, in order to deal with this deterministic and uncertain information, various comprehensive evaluation methods are put forward. In this study, three comprehensive evaluation methods, namely, fuzzy comprehensive evaluation (FCE-AHP), grey relational comprehensive evaluation (GRCE-AHP), and extension matter-element comprehensive evaluation (MECE-AHP), were analyzed and compared in advance, and then the innovative back-propagation neural network comprehensive evaluation (BPCE-AHP) is proposed.

In this paper, fuzzy set theory, variable fuzzy set theory, and variable weight theory are integrated, and a multi-theory integrated comprehensive evaluation method is proposed. The comprehensive evaluation model based on this method is more effective and has stronger adaptability.

4.3. Index Weight Assignment Method

The weighting method is a method used to calculate the weight value of an evaluation index; it cannot directly calculate the evaluation value of each evaluation point, but it can give the relative evaluation value of each evaluation point, that is, the relative advantages and disadvantages of each evaluation point. The following is a trial calculation of 10 groups of sample data; each group contains 10 evaluation points (100 evaluation points in total, as shown in Table 10 of sample data format). Additionally, a comparison chart of the relative evaluation values of the evaluation points of the analytic hierarchy process (AHP), the entropy weight method, the hierarchical entropy weight combination method (AHP-entropy), and the hierarchical fuzzy comprehensive evaluation method II + III + IV (Fuzzy-AHP) is given (Figure 3, giving examples of the first and second groups). The level II + III + IV evaluation value of the fuzzy hierarchy comprehensive evaluation method is equivalent to the relative merits and demerits of each evaluation point, so we take Fuzzy-AHP as a reference and compare it with the entropy, AHP-entropy, and Fuzzy-AHP weighting methods. The closer the shape is, the more accurate and stable the weighting method is. Finally, the merits and demerits of each weighting method and its applicability are analyzed and verified.

Table 10. A group of sample data and format.

Comment Point	Lateral Active Fault Combination	Stereo Structure of Rock Soil Mass	Landform Unit	Terrain Slope (°)	Soil Type in Site	Bearing Capacity of Rock Mass (Mpa)	Soil Compression Coefficient (Mpa^{-1})	Groundwater Level (m)	Groundwater Pollution Index	Permeability (m/d)	Flood Disaster	Seismic Activity (m/s)	Earth Deformation (mm)	Liquefaction of Sand	Fissure in Ground
A1	0.13	0.70	0.78	40.04	0.93	0.91	0.17	18.08	0.44	10.27	0.40	46.46	431.37	0.33	1.00
A2	0.88	0.83	0.66	8.31	0.91	0.02	0.13	21.41	0.52	3.01	0.31	166.77	76.38	0.87	7.00
A3	0.15	0.45	0.60	3.54	0.82	0.27	0.07	27.22	1.04	4.82	0.97	376.86	334.42	0.96	12.00
A4	0.69	0.03	0.42	3.76	0.16	0.57	0.10	8.65	0.08	3.14	0.12	29.28	188.84	0.56	5.00
A5	0.65	0.08	0.86	15.73	0.10	0.82	0.19	15.44	1.23	12.08	0.38	261.79	215.09	0.07	5.00
A6	0.55	0.01	0.96	11.91	0.33	0.69	0.11	23.74	0.51	0.02	0.94	167.43	441.15	0.15	7.00
A7	0.21	0.63	0.21	9.49	0.07	0.18	0.07	8.54	0.67	8.02	0.96	297.23	30.37	0.17	6.00
A8	0.21	0.85	0.49	18.57	0.66	0.80	0.19	21.09	0.82	6.84	0.29	699.95	385.24	0.38	6.00
A9	0.43	0.82	0.40	40.59	0.56	0.34	0.09	4.07	1.27	1.23	0.30	500.38	233.90	0.14	7.00
A10	0.44	0.92	0.48	29.89	0.04	0.94	0.08	22.47	1.14	3.09	0.24	448.95	236.83	0.92	5.00

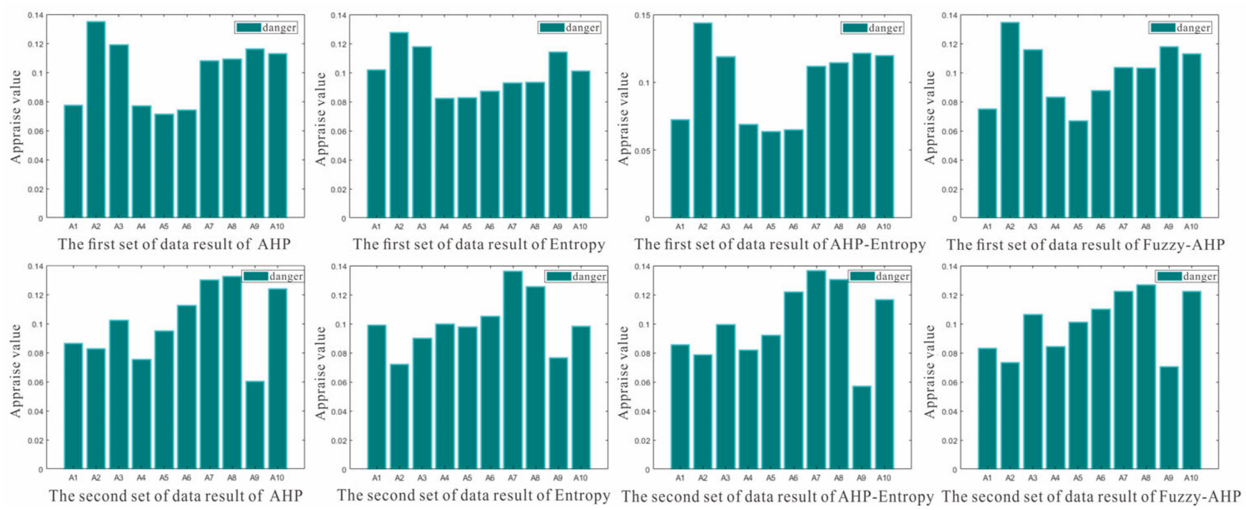


Figure 3. Comparison of the relative evaluation values of each weighting method evaluation point in the first and second groups of samples.

By analyzing the comparison results of the relative evaluation values of the evaluation points of each weighting method in 10 groups of samples, the following conclusions are drawn: the ranking results of the analytic hierarchy process (AHP) and the entropy weighting method are quite different, and the results of AHP-entropy are basically the same as those of AHP, but with some differences. The entropy weight method is highly dependent on data. In the case of insufficient data, it is necessary to be cautious when using the entropy weight method alone, which is generally not recommended. However, when the influence of human factors is relatively small, AHP can always produce satisfactory results for decision makers, so this method should be given priority when assigning weights. The results of the AHP-entropy combination method are close to those of AHP. Considering the influence of subjective and objective factors, the AHP-entropy method is recommended. The ranking results of the AHP and AHP-entropy combination methods are basically consistent with the II + III + IV accumulation results of Fuzzy-AHP, which shows the accuracy of the ranking results.

4.4. Comprehensive Evaluation Method

Because the analytic hierarchy process is stable and reliable, the comprehensive evaluation method is numerically simulated. At the same time, this method is selected as the weighting method. By comparing 10 groups of samples, each group contains 10 evaluation points (100 evaluation points in total), and the safety grade is divided into four grades, which are comprehensively evaluated and calculated. A safety grade evaluation value comparison diagram of the evaluation points (Figure 4) is given; also provided is a safety grade classification comparison diagram of the evaluation points of the Fuzzy comprehensive evaluation method (FCE, namely Fuzzy), the grey relational comprehensive analysis method (GRCE, namely Gray), and the extension matter-element comprehensive evaluation method (MECE, i.e., the matter-element method) (Figure 5), as well as a consistency statistical table of evaluation results (Table 11). Finally, by observing the fluctuating shape of the histogram and the distribution of scattering points and by analyzing the statistical results, the advantages, disadvantages, and applicability of the three weighting methods are verified.

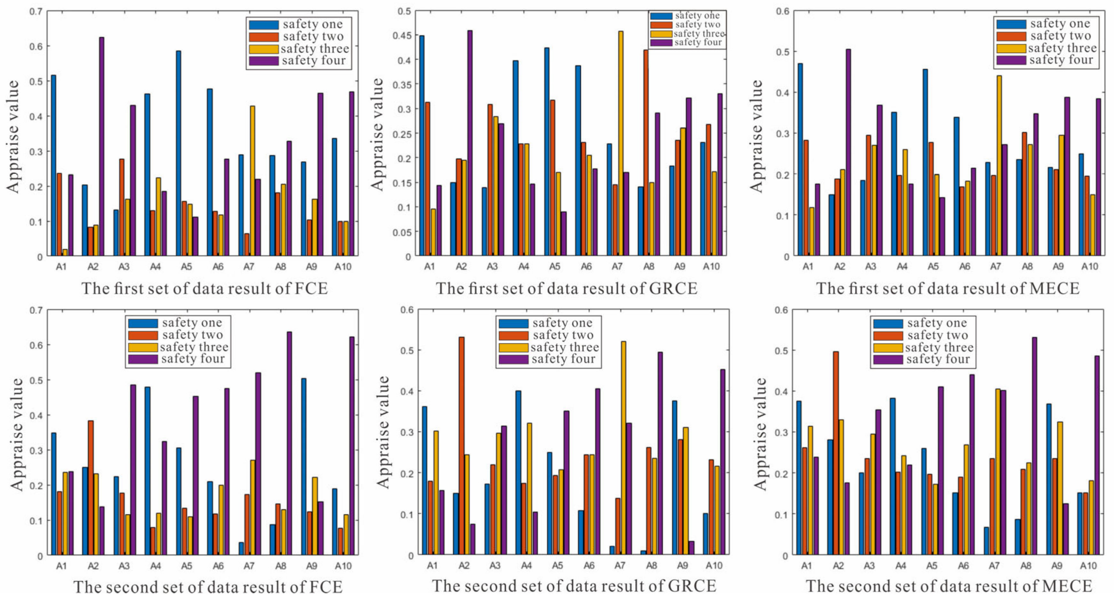


Figure 4. List the comparison of safety grade evaluation values of three comprehensive evaluation methods for the first and second group of samples.

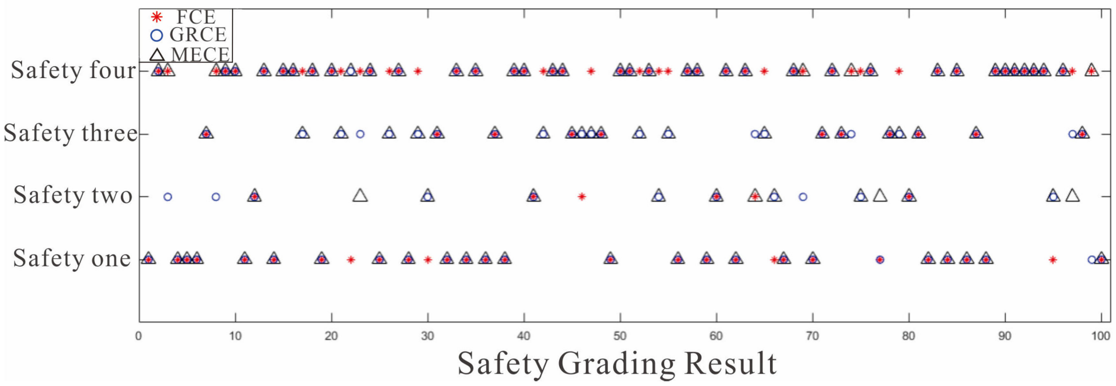


Figure 5. Comparison of safety grade grading of 10 groups of samples with three comprehensive evaluation methods.

Table 11. Statistical table of consistency of evaluation results of three comprehensive evaluation methods for 10 groups of samples.

The Quantity of Data	Identical	Different
FCE and GRCE	75	25
FCE and MECE	80	20
GRCE and MECE	91	9
Three completely different	2	

In addition, a dataset of 20,000 random objective evaluation points is generated by FCE, half of which is used as a training set and half as a test set. This is used to verify the correctness, feasibility, advantages, and disadvantages of back-propagation neural network comprehensive evaluation (BPCE).

4.4.1. FCE, GRCE and MECE Numerical Simulation Tests

Based on the comparison results of the evaluation of 10 groups of samples (100 evaluation points in total) (Figures 4 and 5) and consistency statistics (Table 11), we draw the following conclusions: the similarity of FCE, GRCE, and MECE is over 75%, and the evaluation results of GRCE and MECE are more similar, which is consistent with the evaluation system whereby both theories are partially linear. MECE is closer to FCE than GRCE, and the classical domain partition of MECE is closer to the membership function partition of FCE than the reference sequence partition of GRCE, which is also consistent with the theory. The membership function of FCE is flexible and changeable and can choose a linear or curved type, which is more suitable for the evaluation of nonlinear systems. It is the best of the three methods, followed by the matter-element method. However, these three methods still constitute subjective weighting comprehensive evaluation methods, which are inevitably influenced by interference of human factors, resulting in inaccurate evaluation results.

4.4.2. BPCE Numerical Simulation Test

The Back-Propagation Neural Network Comprehensive Evaluation (BPCE) method is an objective weighted evaluation method. Artificial neural networks have become the most promising comprehensive evaluation method because of their self-organization, self-learning, and self-adaptation capabilities, nonlinear mapping, strong fault tolerance, and fast operation speeds.

Due to the lack of actual sample data, we use the FCE (FCE-AHP) method to uniformly and randomly generate 10,000 training data and 10,000 test data. The BPCE comprehensive evaluation method generates a safety evaluation network model through BPNN neural network training, and then uses the network model to evaluate the test data to obtain the evaluation results. This BPCE result uses a 3-layer network model with 1 hidden layer and 128 hidden nodes. Below, a comparison diagram of the BPCE and FCE safety level evaluation values for the training data (Figures 6–9) and a histogram of the error frequency distribution of the evaluation values (Figure 10) are given. The comparison diagram of the BPCE and FCE safety grade evaluation values for the test data (Figures 11–14) and the histogram of the error frequency distribution of the evaluation values (Figure 15) are used to verify the correctness, feasibility, advantages, and disadvantages of the BPCE neural network's comprehensive evaluation method, by observing the coincidence of the evaluation values and the distribution of the evaluation errors.

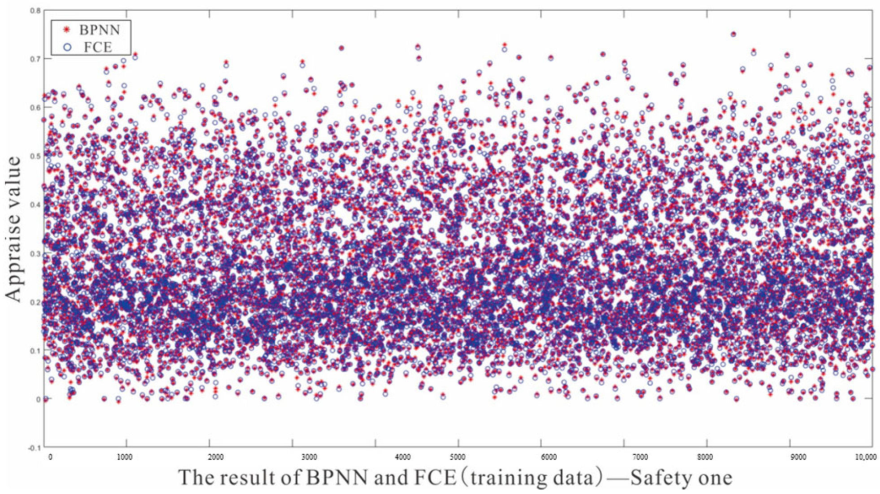


Figure 6. Training data—comparison of BPCE and FCE evaluation values (safety level I).

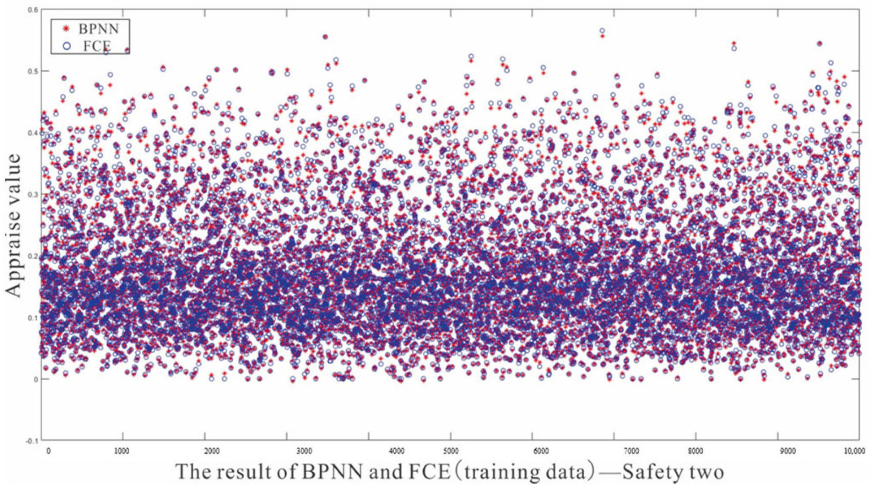


Figure 7. Training data—comparison of BPCE and FCE evaluation values (safety level II).

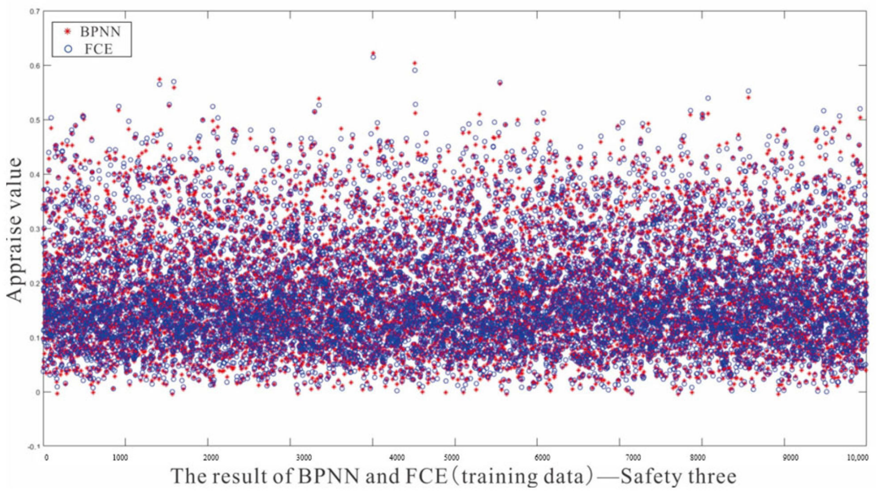


Figure 8. Training data—comparison of BPCE and FCE evaluation values (safety level III).

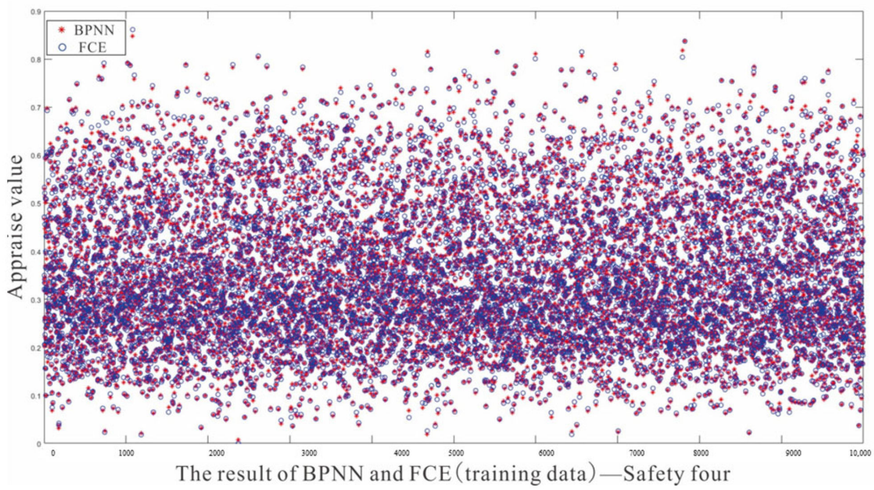


Figure 9. Training data—comparison of BPCE and FCE evaluation values (safety level IV).

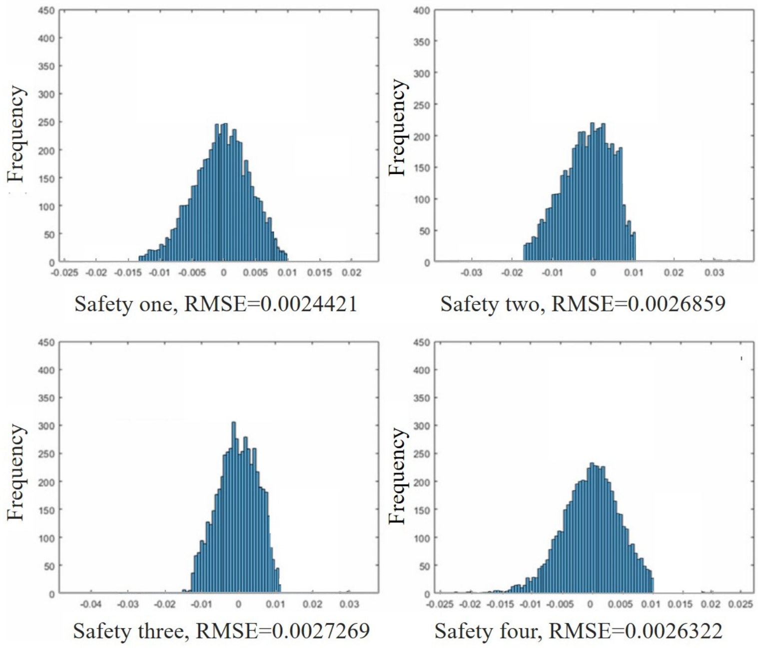


Figure 10. Training data—BPCE and FCE evaluation error frequency distribution histogram.

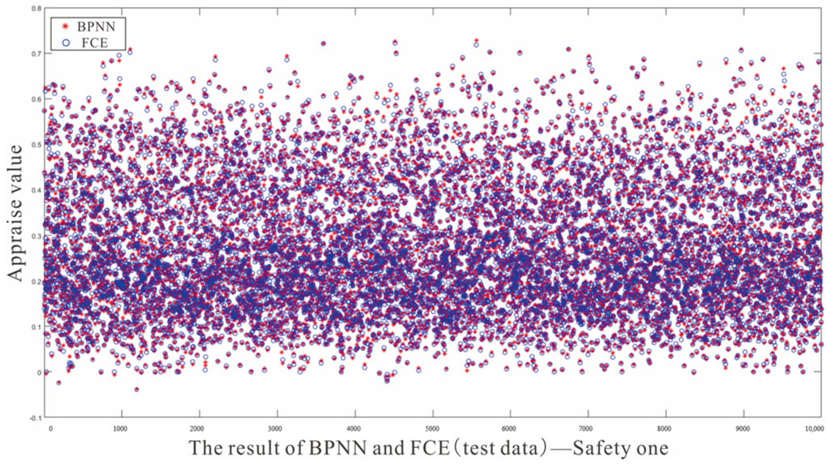


Figure 11. Test data—comparison diagram of BPCE and FCE evaluation values (safety level I).

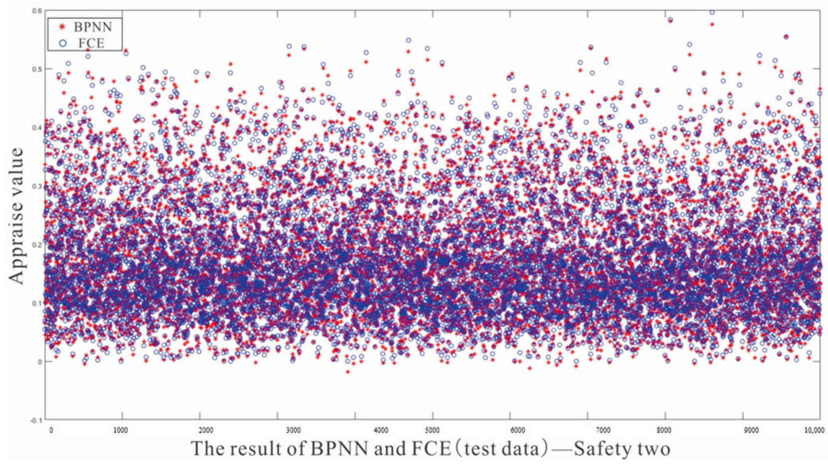


Figure 12. Test data—comparison of BPCE and FCE evaluation values (safety level II).

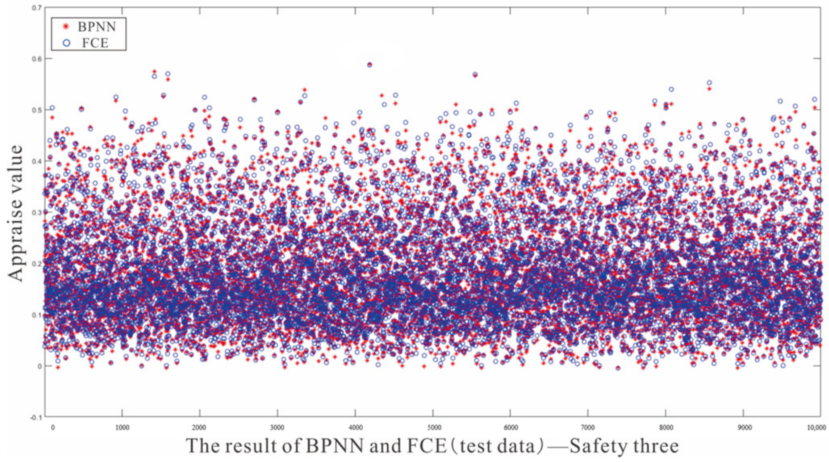


Figure 13. Test data—comparison of BPCE and FCE evaluation values (safety level III).

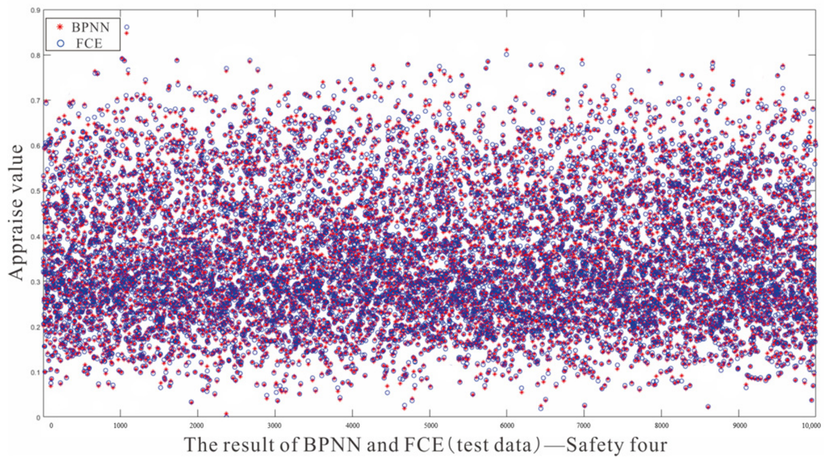


Figure 14. Test data—comparison diagram of BPCE and FCE evaluation values (safety level IV).

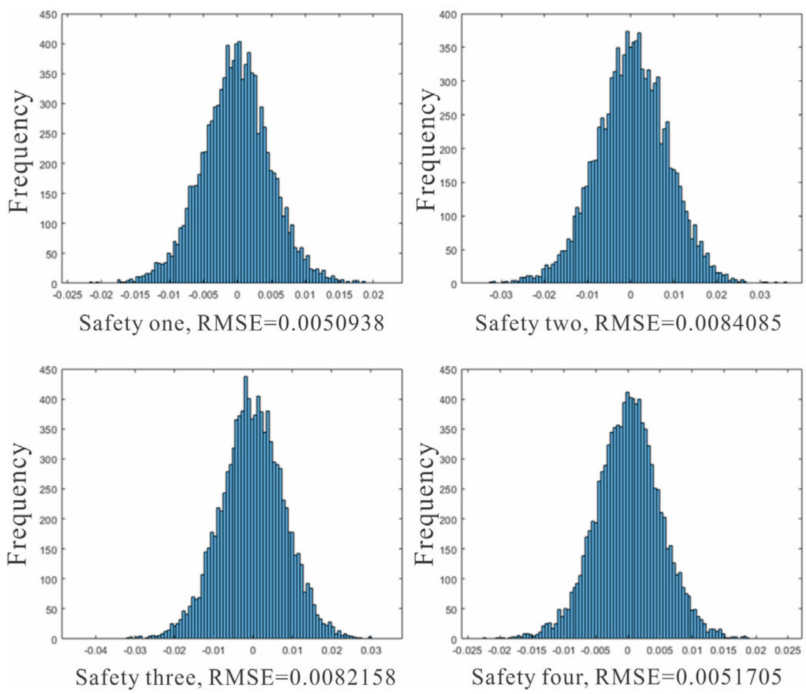


Figure 15. Test data—BPCE and FCE evaluation error frequency distribution histogram.

According to the results of Figures 6–9 and Figures 11–14, the BPCE evaluation values for the training data and the test data almost coincide with the FCE evaluation values. In Figure 10, the root mean square errors of BPCE and FCE safety I–IV are 0.0024, 0.0027, 0.0027, and 0.0026, respectively, and the root mean square errors less than 0.01 account for 100%, 99.97%, 99.99%, and 99.99%. In Figure 15, the root mean square errors of BPCE and FCE safety I–IV are 0.0051, 0.0084, 0.0082, and 0.0052, respectively, and the root mean square errors less than 0.01 account for 97.63%, 87.96%, 89.61%, and 97.22%. The final safety classification error rate is nearly one thousandth, which is almost unaffected.

Through the preceding evaluation comparison, we can see that BPCE is fully capable of restoring and replicating FCE. Theoretically, as long as there are enough training data, hidden layers, and hidden nodes, it can approximate any nonlinear mapping relationship. Therefore, BPCE is the safety evaluation model that is closest to reality.

However, the practical application of BPCE faces significant challenges. First, real training data are often difficult to obtain; second, with the increase in the number of hidden layers and nodes, the training speed of the network decreases rapidly, which takes up a lot of resources. However, we propose that BPCE represents the main research direction for comprehensive evaluation methods in the future.

5. Geological Safety Evaluation

Qingdao is characterized by coastal mountainous landforms and is prone to or may experience geological environmental problems such as land subsidence, seawater erosion, earthquakes, floods, landslides, and so on. Referring to the geological safety evaluation index system of underground spaces in coastal cities, the geological safety of the study area is evaluated using the above methods (Figures 16–19).

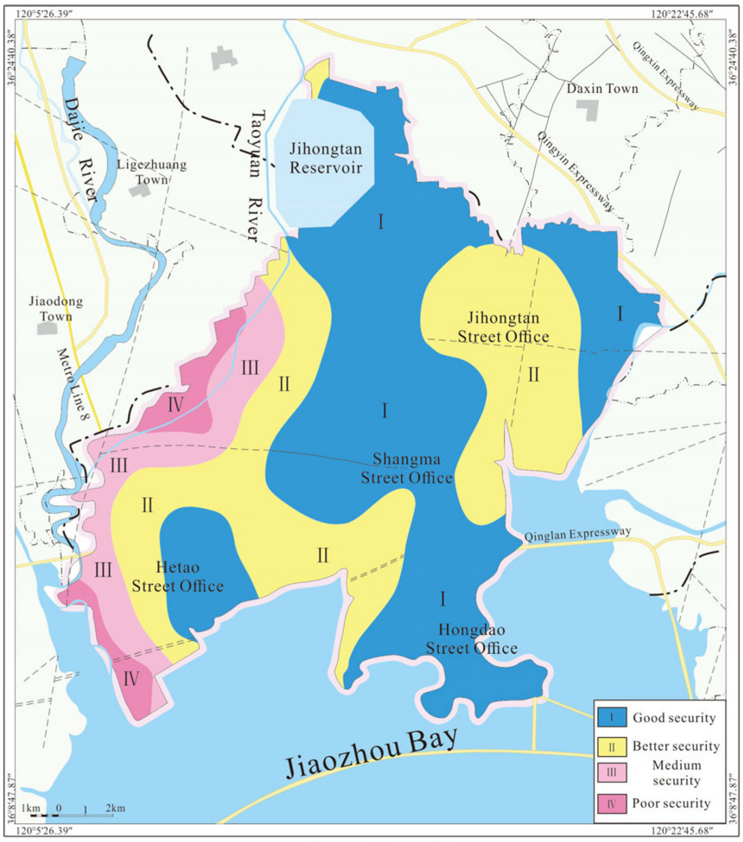


Figure 16. Geological security zoning of FCE-AHP underground space at a depth of 0–30 m in Hongdao Economic Zone.

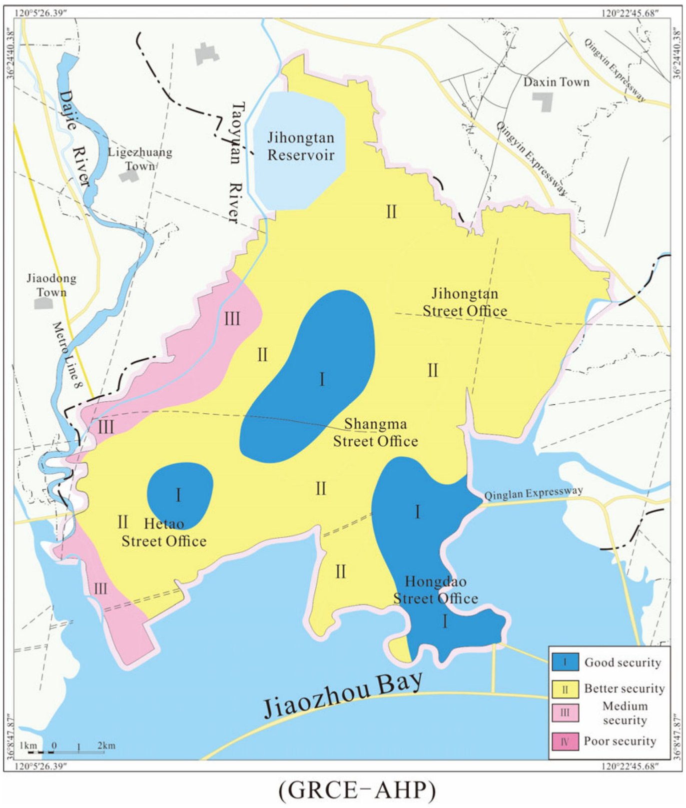


Figure 17. Geological safety zoning map of GRCE-AHP underground space at a depth of 0–30 m in Hongdao Economic Zone.

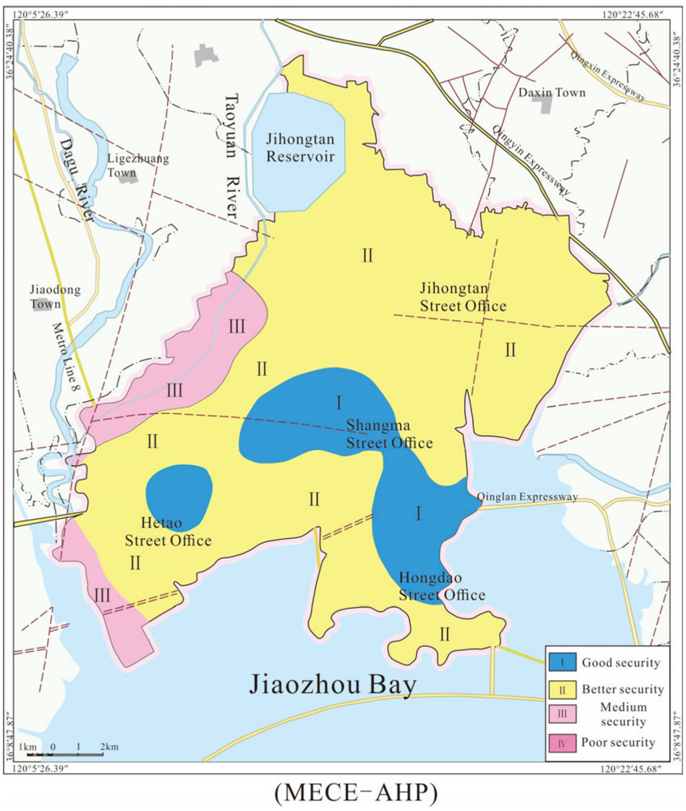
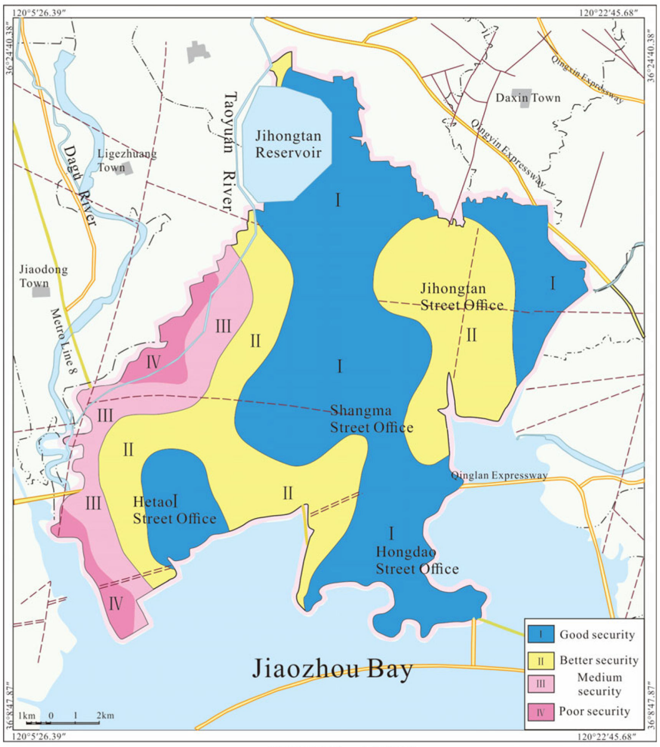


Figure 18. Geological safety zoning map of MECE-AHP underground space at a depth of 0–30 m in Hongdao Economic Zone.



(BPCE−AHP)

Figure 19. Geological Safety Zoning Map of BPCE-AHP Underground Space (0–30 m) Shallow at 0–30 m in Hongdao Economic Zone.

Comparing the evaluation results, we can see that the evaluation results of FCE-AHP, GRCE-AHP, and MECE-AHP are similar; the results of GRCE-AHP are closer to those of MECE-AHP, and the results of MECE-AHP are closer to those of FCE-AHP. The results are completely consistent with the numerical simulation results. The essential reason for this is that the reference sequence of GRCE-AHP is often difficult to produce artificially. Similarly, although the classical domain of MECE-AHP has changed from the reference point of GRCR to the reference range, it is still difficult to describe complex nonlinear systems. FCE-AHP more easily characterizes complex nonlinear systems through its flexible membership function design, and it can often give satisfactory evaluation results. The results of FCE-AHP and BPCE-AHP are completely identical, and the neural network evaluation model of BPCE-AHP is trained from the results of FCE-AHP. Therefore, this result shows that, if we provide a lot of actual data, such as 10,000 evaluation points, after the training of the algorithm, BPCE-AHP can further optimize the neural network evaluation model and the evaluation effect of BPCE-AHP will surpass that of FCE-AHP.

The BPCE-AHP method is a comprehensive evaluation method that integrates multiple theories. Compared with other common comprehensive evaluation methods, this method is more suitable for evaluating the geological safety of urban underground space and conducting the comprehensive evaluation of other complex systems.

The evaluation results of five collapse points of Metro Line 2 are verified. The landform type of Metro Line 2 is relatively simple, and the stratum structure is relatively clear. The regional tectonic background of Metro Line 2 is stable, the adverse geological effects are not developed, and the site's stability is good. However, the groundwater is corrosive to concrete structures. The verification results of the five collapse points are consistent with the evaluation results of the BPCE-AHP comprehensive evaluation method. Therefore, the effectiveness of the BPCE-AHP comprehensive evaluation method is proven.

6. Conclusions

1. According to the geology, hydrogeology, engineering geology, and adverse geological action of the study area, following scientific and reasonable principles, and considering the hierarchy, diversity, fuzziness, and uncertainty of the evaluation index system, a high-quality comprehensive index system for evaluating the geological environmental safety of underground space development in coastal bedrock cities is optimized and established.
2. Based on a variety of comprehensive evaluation algorithms and a numerical simulation, the research results show that FCE-AHP is more suitable for the evaluation of complex nonlinear systems, GRCE-AHP is more suitable for the evaluation of simple linear systems, and MECE-AHP's performance level is between FCE-AHP and GRCE-AHP. However, these three methods inevitably involve human interference, which leads to inaccurate evaluation results; BPCE-AHP can produce the most realistic safety evaluation model. By adjusting the parameters of the comprehensive evaluation model and designing the membership function, this method can accurately describe complex systems.
3. Back-propagation neural network comprehensive evaluation (BPCE) constitutes an objective comprehensive evaluation method. It can avoid human interference and surpass FCE and has broad development and application potential. A suitability evaluation of underground space development was carried out in the Hongdao Economic Zone, and the evaluation results were verified by the collapse point of Qingdao Metro Line 2. This effectively proved the practicability and effectiveness of the BPCE-AHP comprehensive evaluation method; ultimately, it verified that the BPCE-AHP evaluation results are scientific, reasonable, and reliable in evaluating the geological safety of underground space in coastal bedrock cities.

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Data Availability Statement: All data can be provided upon contacting the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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