

Article

Suitability Evaluation of Urban Underground Space Development: A Case Study of Qingdao City

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Abstract: Urban underground space, as an underutilized land resource, holds tremendous potential and value. Efficient and rational development and utilization of this resource are key to addressing current urban challenges. This study takes the main urban area of Qingdao City as an example and establishes a comprehensive evaluation system for the suitability of urban underground space development at different depth levels through the integration of geological, hydrological, and urban planning factors. By utilizing the Analytic Hierarchy Process to assign weights to evaluation criteria within the system, both a multi-objective linear weighting function model and a fuzzy comprehensive evaluation model are employed to assess the suitability of underground space development. The results delineate the distribution of underground space development suitability within the study area. Comparative analysis of the two models reveals that the fuzzy comprehensive evaluation model offers a more detailed and comprehensive reflection of the complexity and diversity of underground space development, providing forward-looking and insightful evaluation results for urban planning and development. The evaluation indicates that certain streets within the main urban area of Qingdao exhibit excellent prospects for underground space development.

Keywords: urban underground space; suitability evaluation; fuzzy comprehensive evaluation; analytic hierarchy process with variable weights; Qingdao City



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1. Introduction

In the accelerating process of urbanization, evaluating the suitability of urban underground space development becomes increasingly critical. With the rapid increase in urban population, land resources are becoming increasingly scarce, and traditional urban development models struggle to meet demands, exacerbating urban issues [1]. Assessing the development potential of urban underground space not only maximizes the utilization of limited land resources but also alleviates surface congestion and resource scarcity, enhancing overall urban quality of life and environmental standards. Moreover, it contributes to promoting sustainable urban development by scientifically planning and utilizing underground space, improving resource efficiency, and reducing energy consumption and environmental pollution. Furthermore, evaluation results serve as vital references for urban planning, guiding the rational utilization of underground space and ensuring the city's long-term goals and sustainability. In summary, conducting evaluations of urban underground space development suitability is an indispensable measure for addressing

urban land resource scarcity, mitigating urban issues, promoting sustainable development, and guiding urban planning [2].

Many scholars have evaluated the suitability of urban underground space development from various perspectives [3]. Some methods require the functions of the city's underground space, such as some underground structures, while others are mainly based on the engineering geological conditions of the underground and the urban planning demand conditions above ground. Currently, the majority of research on factors influencing the evaluation of urban underground space development suitability is divided into two main aspects: engineering geological conditions and urban planning requirements [4–6]. In terms of engineering geology, for example, in the underground space planning of the Minneapolis-Saint Paul area, Sterling et al. [7] conducted a thorough examination of the influence of factors such as stratum distribution, hydrogeological conditions, and topography by conducting an overlay analysis of these factors to determine the distribution of suitability for underground space development within the study area. In the study of underground space land use planning in Finland, Ronka et al. [8] developed a model for assessing the suitability of underground space development, focusing on excavation challenges across various rock layers. Boivin et al. [9] utilized the transparent overlay method to examine the engineering geological conditions in the designated region, determining the distribution range and capacity of available underground space in the Quebec region of Canada and assessing its development difficulty. Rienzo et al. [10] proposed a GIS-based 3D geological structure model, which has been applied in the planning and management of urban underground space development. Wang et al. [11] have devised a model for evaluating geological suitability for urban underground space development, focusing on engineering geology and site stability among other aspects. This model has been applied to the urban underground space development planning in Changzhou, China.

In addition to engineering geological conditions, urban planning factors also play a crucial role in decision-making regarding urban underground space development [12–15]. Bobylev [16] studied population density and urban underground space construction volume correlations in Stockholm, Paris, and Tokyo. The findings indicate that areas with higher population densities tend to have larger-scale urban underground space development. He et al. [17,18], examining Shanghai's districts and counties as case studies, explored the relationship between underground space development intensity and three urbanization indicators: per capita GDP, population density, and housing prices. Findings from the experiments indicate a robust correlation between population density and per capita GDP with the intensity of underground space development. Wang et al. [4] concluded, based on an analysis of factors influencing urban underground space development, that commercial land prices, economic location, economic development status, geological conditions, and compatibility with urban planning are the five main influencing factors of underground space development. Peng et al. [19], taking Wuhan's Yangtze River New Town as a case study, suggested that urbanization indicators closely linked to urban planning and socio-economic conditions play significant roles in determining the intensity of urban underground space development.

The selection of appropriate methods and models for evaluating urban underground space suitability is crucial, and it should be based on a comprehensive consideration of specific evaluation purposes, data availability, and research objects. Youssef et al. [20] developed an Analytic Hierarchy Process-based model for evaluating suitability, considering engineering geological conditions. Durmisevic et al. [21], in their study of underground station construction, conducted a comprehensive analysis using neural network algorithms and subsequently developed a suitability evaluation model for underground stations. Dou et al. [22], in an effort to boost the precision of suitability assessment outcomes, proposed a TOPSIS system for evaluating the suitability of underground space development, leveraging the grey relational model. Li et al. [23] employed fuzzy comprehensive evaluation methods to assess the construction risks of a proposed subway station in Ningbo, China. Peng [24] proposed an indicator system and analytical process for assessing urban un-

derground space development, employing mathematical techniques like the Worst Case Scenario method and the Exclusion method. This methodology has been implemented in the evaluation of urban underground space development in cities such as Tongren, China. Zhou et al. [25] applied the Analytic Hierarchy Process (AHP) to create a suitability assessment model for urban underground space development in Nantong, China. This allowed for a thorough evaluation of the feasibility, value, and quality of utilizing underground space resources. Zhang et al. [26] quantitatively analyzed the compatibility between surface and underground spaces in Shenzhen, China, and employed an enhanced Artificial Intervention Genetic Algorithm to construct an evaluation model for underground space development, aiming to achieve optimal two-dimensional planning solutions. Xu et al. [27] employed a Bayesian Network model as a decision support tool, and researchers assessed the suitability of underground space development in Changsha, China. They also established a corresponding spatial database to streamline the assessment process. Dou et al. [28] put forward a suitability evaluation framework based on three-dimensional geological data. This framework integrates geological data with 3D technology and has been implemented in the geological suitability assessment of underground space development in Qianjiang New Town, Hangzhou, China.

In summary, urban planning is a very complex issue that needs to collect data on the functions of the city's underground space, such as some underground structures. These existing underground structure data can be used to properly verify the evaluation results and provide some guidance, such as those used by Mavrikos et al. [29], where a comprehensive approach to the feasibility of underground space development was proposed. On the other hand, many scholars, such as Sterling et al. [7], Boivin et al. [9], Rienzo et al. [10], Youssef et al. [20], and Durmisevic et al. [21], have taken another approach when evaluating the suitability of urban underground space development. This method is based on the engineering geological conditions of the underground in the study area and the urban planning demand conditions above ground and evaluates the suitability of urban underground space development based on various factors. This method is also a commonly used method to evaluate the development potential of underground space, which is also used in this study.

Due to the lack of land resources in Qingdao's main urban area due to the excessive mountain area and its important economic and strategic location, the development of underground space is very important. Therefore, this paper chose Qingdao as the research area. Different from previous studies, this study also integrated the engineering geological conditions and urban planning requirements of the study area and conducted in-depth research and analysis on various factors affecting underground space development in the main urban area of Qingdao, China, including geological conditions, surface construction status, and urban planning requirements. After selecting influential factors that impact underground space development, the study used them as evaluation indicators for assessing the adaptability of urban underground space development [30]. Based on these indicators, suitability evaluation systems for shallow and medium-depth underground space development in Qingdao were constructed. The study then assigned weights to the indicators in the evaluation system and compared the weight assignment results obtained from different methods. There are many kinds of data used in the evaluation system, so there are some errors in the evaluation results when using these data for suitability evaluation. In order to reduce the impact of these errors on the evaluation results, both a multi-objective linear function weighting model and a fuzzy comprehensive evaluation model are utilized to evaluate the suitability of urban underground space development in Qingdao's main urban area, followed by a comparative analysis of the evaluation results. In recent years, fuzzy logic has emerged as a vital tool in various fields due to its unique advantages in handling complex and uncertain environments. For instance, Rodríguez-Pérez et al. [31] utilized fuzzy logic to analyze the feasibility of tidal turbine installations. Their research demonstrated the robustness of fuzzy logic in addressing multiple uncertainties, such as tidal forces, environmental impacts, and economic viability. By considering these

factors holistically, fuzzy logic provided a reliable assessment tool, enabling researchers to conduct more precise feasibility analyses in complex natural settings. This example illustrates that fuzzy logic, as a method for managing complexity and uncertainty, holds broad application prospects. This study aims to build on these successful experiences by further exploring the application of fuzzy logic in the evaluation of the suitability of underground space development, providing new perspectives and methodologies for the relevant field. Ultimately, drawing from the evaluation findings, the study offers a scientific foundation and guidance for the future planning of underground space development in Qingdao. Scientific and reasonable evaluation of the suitability of underground space development is of great significance to the future development of cities.

2. Overview of the Research Area

Qingdao is located in the eastern coastal region of Shandong Province, China, with geographical coordinates ranging from approximately 36°03' to 37°25' north latitude and 119°30' to 121°00' east longitude. It borders the Yellow Sea to the east, Jiaozhou Bay to the west, Qingdao Bay to the south, and the Laoshan Mountains to the north. The scope of this study encompasses the primary urban zone of Qingdao, comprising five districts: Shinan District, Shibei District, Licang District, Laoshan District, and Chengyang District, spanning a total land area of 669.767 km². Given Qingdao's recent rapid growth, the strategic development of urban underground space has emerged as a pivotal approach for achieving sustainable progress and enhancing urban living standards [32]. The precise research scope is depicted in Figure 1.

The terrain of the study area generally slopes from east to west, with the western areas such as Cangkou and Chengyang being relatively flat, belonging to the marginal area of the Jiaolai Alluvial Plain, with elevations mostly ranging from 10 to 60 m above sea level. The eastern part comprises low mountains and hills, with elevations mostly between 400 and 800 m. The geological structures in the study area include several brittle faults, among which Cangkou, Pishikou, and two northeast-oriented faults are the most typical. The engineering mechanical properties are relatively poor, with soft soil layers characterized by silt and fine sand mainly distributed in the northwest part of the study area (around Liuting) in the floodplain areas of Baisha River and Moshui River, as well as in the river valley sections of Beizhai and Qinjiatuzhai. The core urban areas, such as Shinan District, Shibei District, and Licang District, have high population densities and abundant commercial, cultural, and educational resources. Core commercial areas along the southern coast, such as Xinhaoshan Commercial District and the surrounding areas of May Fourth Square, also boast high commercial land prices.

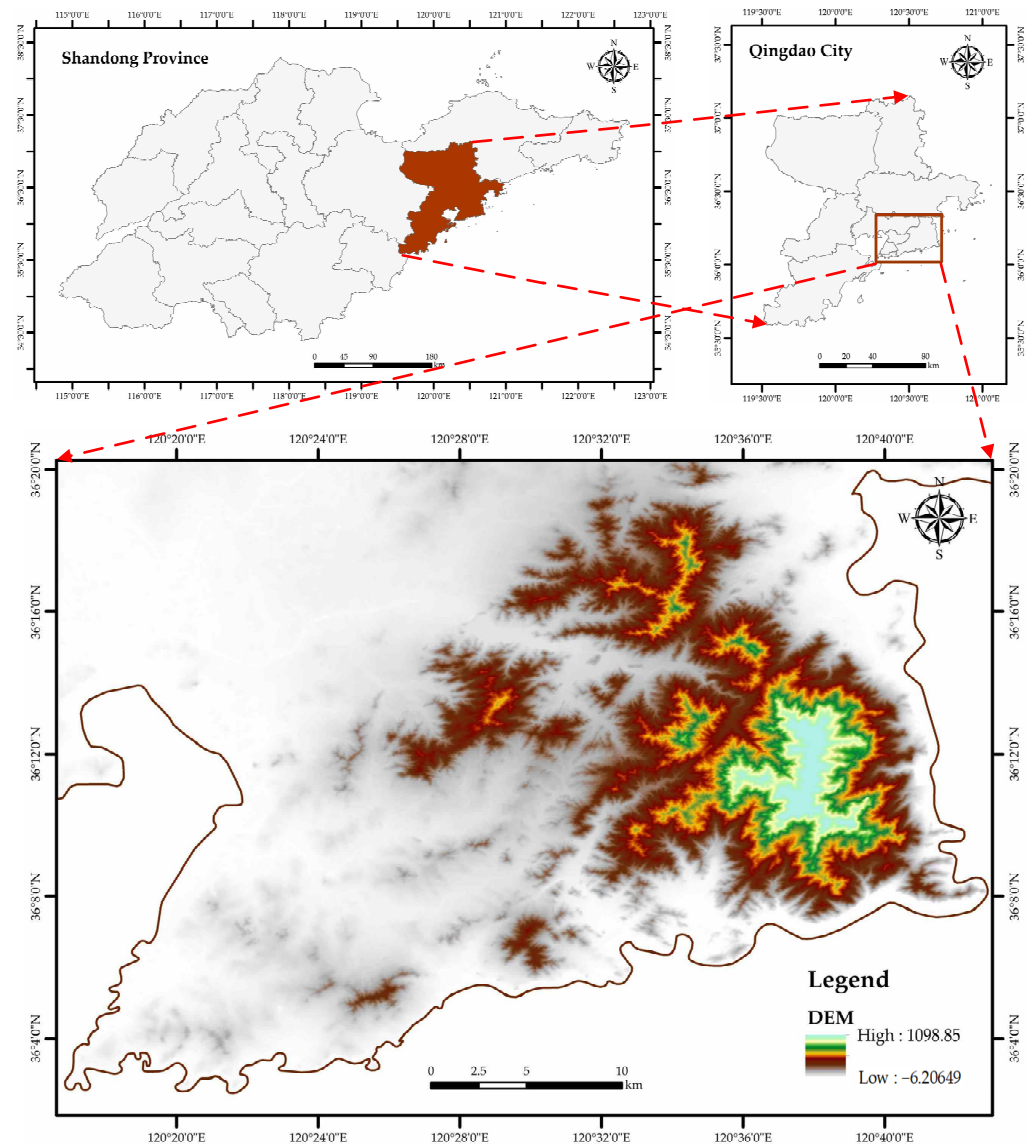


Figure 1. Overview of the location of the study area.

3. Research Method

After gathering and preprocessing data related to geological conditions, hydrological conditions, urban planning conditions, and other relevant factors within the study area, a comprehensive analysis was conducted to identify factors influencing urban underground space development. Six major influencing factors and thirteen evaluation indicators were subsequently selected for the suitability assessment of urban underground space development. These factors encompass terrain and landforms, engineering geological conditions of rock and soil, adverse geological effects and fractures, hydrogeological conditions, existing construction conditions, and urban planning requirements. The detailed evaluation process is depicted in Figure 2.

3.1. Construction of Suitability Evaluation System

The degree of influence of various factors on urban underground space development varies according to the depth of evaluation, as determined by analyzing various influencing factors and adhering to the principles of constructing evaluation systems. Therefore, this paper divides the evaluation indicator system into two depth levels: shallow underground space (0–10 m) and medium-depth underground space (10–60 m). The framework of the

suitability evaluation indicator system is illustrated in Figures 3 and 4. The main data sources used in this study are shown in Table 1.

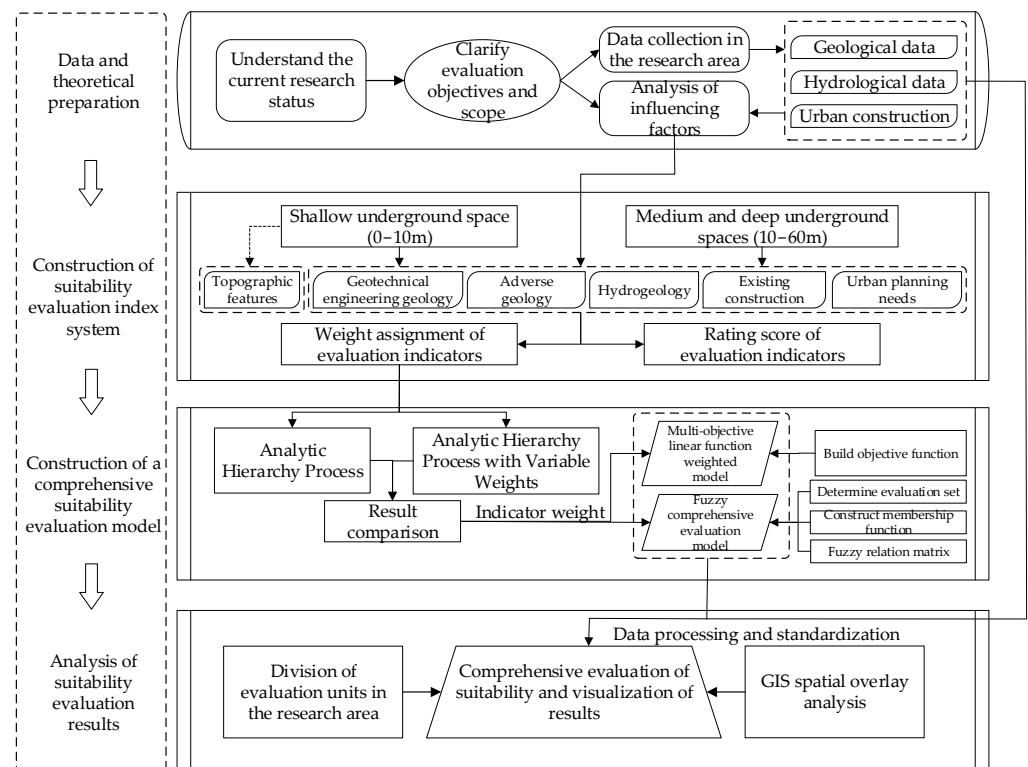


Figure 2. Technical flowchart for suitability evaluation of urban underground space development.

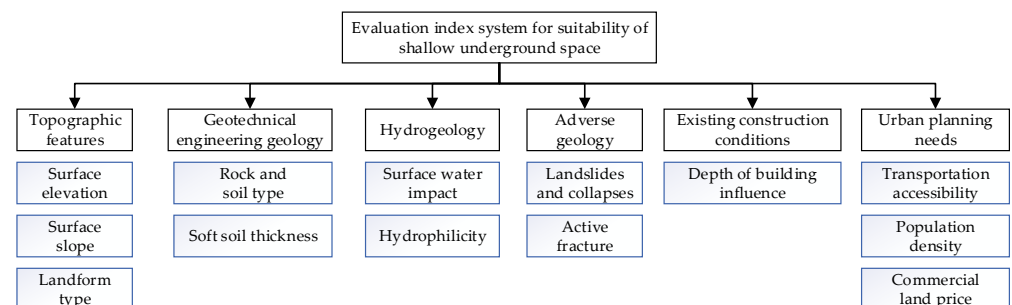


Figure 3. Suitability evaluation index system for shallow underground space.

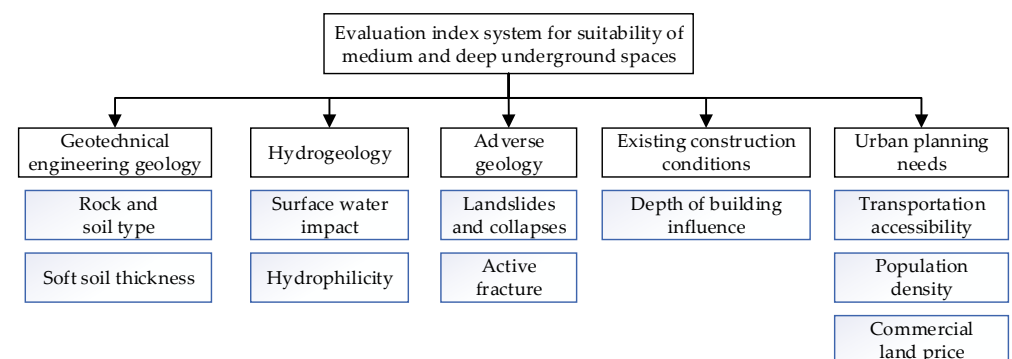


Figure 4. Suitability evaluation index system for deep underground space.

Table 1. Main data sources.

Number	Data Name	Data Sources	Data Type
1	30 m resolution DEM	USGS	Grid
2	Landform type		Grid
3	Fault distribution	China Geological Survey Bureau	Grid
4	Rock and soil type		Grid
5	Distribution of soft soil layers		Grid
6	Surface water system	Standard Map of Shandong Province	Vector
7	Groundwater water richness	China Geological Survey Bureau	Grid
8	Distribution of geological hazards		Vector
9	Ground building height	China Resource Satellite Application Center	Vector
10	Road and underground rail transit	National Basic Geographic Information Center	Vector
11	Population density	National Bureau of Statistics	Grid
12	Land price	China Land Price Information Service Platform	Grid

This paper, by referencing the relevant regulations on construction land and underground space planning in Chongqing and Shenzhen, combined with the actual geological environment of the study area, has developed quantitative grading standards applicable to the evaluation indicators for this study area. Following the “Standards for the Evaluation of Urban and Rural Construction Land”, the suitability of underground space development in Qingdao’s main urban area is categorized into four levels: highly suitable, moderately suitable, generally suitable, and unsuitable regions. Upon standardization, these levels correspond to numerical values ranging from 0 to 1, where higher scores denote greater suitability for development. The specific grading and scoring systems are presented in Table 2.

Table 2. The grading and scoring systems of evaluation indicators in the main urban area of Qingdao City.

Evaluating Indicator	Score			
	0.75–1	0.5–0.75	0.25–0.5	0–0.25
Surface elevation	<100	100–300	300–500	>500
Landform type	Erosion and accumulation quasi plain	Structural erosion of low mountains and hills	Mountain valley impact plain	Moderate to shallow cutting in low to medium mountainous
Slope	0–5	5–14	14–31	>31
Rock and soil type	Excellent	Good	Medium	Bad
Soft soil thickness	None	<3.5	<10	<15
Surface water	Non-buffer zone	-	-	Buffer zone
Hydrophilicity	<100	100–500	500–3000	>3000
Disasters such as landslides and collapses	Non-buffer zone	-	-	Disaster point buffer zone
Active fracture	Non-buffer zone	-	-	Fault zone buffer zone
Depth of influence of surface buildings	None	0–10	10–50	>50
Transportation accessibility	Subway hub	Subway Station	Road	Others
Population density	Very dense	Slightly dense	Commonly	Rare
Land price	>30 k	20–30 k	10–20 k	<10 k

3.2. Weight Assignment of Evaluation Indicators

Determining the weights of evaluation indicators is a crucial process in multi-objective decision-making. The rationality of indicator weights is closely related to the rationality of evaluation results. Any change in the weight of each indicator will affect the final evaluation results. Therefore, it is essential to find appropriate methods for assigning

weights to ensure the scientific and objective nature of the evaluation process. In this study, the Variable-Weight Analytic Hierarchy Process (VWAHP) method, which incorporates the concept of variable weights, was employed. This method overcomes the shortcomings of the traditional Analytic Hierarchy Process (AHP) [33], where fixed weights may lead to biased evaluation results.

The concept of variable weights was initially proposed by Chinese scholar Professor Wang Peizhuang in 1980 [34]. The introduction of variable-weight models aimed to address the limitations of traditional fixed-weight models in dealing with complex and dynamic decision-making environments, providing a more flexible and adaptable decision-making tool. The Variable Weight Analytical Hierarchy Process (VWAHP) adjusts weights based on varying conditions. First, define the hierarchy and criteria; then, construct pairwise comparison matrices and calculate initial weights; next, adjust weights dynamically according to specific conditions or contexts; then, recalculate the priority vectors and consistency; finally, aggregate the adjusted weights to determine the optimal decision. Considering the tendency of the suitability evaluation of urban underground space development to generate neutral effects, the variable weight model constructed in this study dynamically adjusts the weights of various decision factors by introducing a penalty mechanism. This is achieved by constructing the variable weight model based on the idea of penalizing factors with poor performance. The variable weight model $W(X) = (w_1(x), w_2(x), \dots, w_n(x))$ indicates that $W(X)$ possesses n dimensions, $w_i (i = 1, 2, \dots, n)$, $W_i: [0, 1]^n \rightarrow [0, 1]$, $(x_1, x_2, \dots, x_n) \mapsto w_i(x_1, x_2, \dots, x_n)$. The main idea of the Variable-Weight Analytic Hierarchy Process (VWAHP) is to introduce a variable weight model into the traditional Analytic Hierarchy Process (AHP). Initially, the AHP is used to determine the initial weights W^0 of evaluation indicators. Then, based on the specific research conditions, a local state variable weight function $Y(X)$ is constructed. The normalized product of these two vectors yields the variable weight vector $W(X)$. This approach adjusts the weights of evaluation factors according to different evaluation areas.

$$W(X) = \frac{(w_1^0 \cdot Y_1(X), w_2^0 \cdot Y_2(X), \dots, w_n^0 \cdot Y_n(X))}{\sum_{i=1}^n (w_i^0 \cdot Y_i(X))} = \frac{W^0 \cdot Y_i(X)}{\sum_{i=1}^n (w_i^0 \cdot Y_i(X))} \quad (1)$$

To ensure more objective and rational weight allocation, this study systematically investigated the principle of local variable weighting based on previous experiences. Combining decision-makers' preferences, an improved local indicator state variable weight function $Y(X)$ was proposed. The core idea behind constructing the variable weight function in this study is to increase the weight of indicators with lower suitability evaluation grades while keeping the weights of indicators with higher suitability evaluation grades unchanged. The goal is to amplify the impact of adverse factors on the evaluation area, reduce the scores in areas with lower-grade indicators, and thereby establish a penalty-based variable weight model that exceeds the incentive, making the evaluation results more scientifically reasonable. The axis X of the constructed state variable weight function represents the magnitude of a certain indicator value within the evaluation unit, ranging from 0 to 1. In the first interval $[0, a]$, due to the very low rating of the indicator, it requires extremely severe penalties, and the growth rate of the state variable weight function increases as the indicator value decreases. In the interval $[a, b]$, the penalty is significantly reduced compared to the previous interval, and in the interval $[b, c]$, the rate of change of the state variable weight function decreases as the indicator value increases. When the indicator value is greater than c , the value of the state variable weight function remains unchanged. The constructed function graph is shown in Figure 5.

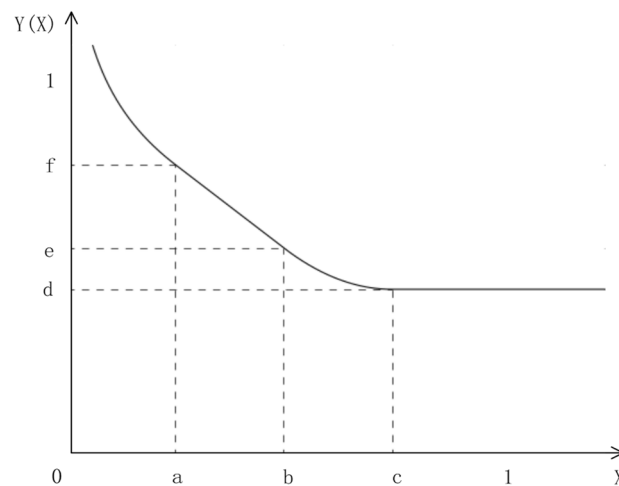


Figure 5. Local state variable weight function.

Among them, a , b , and c represent the indicator values at the node, while d , e , and f represent the function values of the state variable weight function. Based on the characteristics of the state variable weight function mentioned above, the specific functions obtained are as follows:

$$Y(X) = \begin{cases} \frac{f-e}{b-a} \cdot a \ln \frac{a}{x_i} + c, & x_i \in (0, a) \\ \frac{e-f}{b-a} x_i + \frac{f \cdot b - e \cdot a}{b-a}, & x_i \in (a, b) \\ \frac{e-d}{(c-d)^2} (c - x_i)^2 + d, & x_i \in (b, c) \\ d, & x_i \in (c, 1) \end{cases} \quad (2)$$

The determination of parameter values for the variable weight status function is a critical factor in assessing the scientific validity of weight calculation results. The segmentation of interval ranges is initially based on the grading score system established in the previous section for the degree of influence of factors. Specifically, we set $a = 0.25$, $b = 0.5$, $c = 0.75$, dividing the indicator values into four intervals. Considering the characteristics of the variable weight status function and its derivative discussed in the preceding section and integrating the features of urban underground space development in Qingdao City and the developed underground spaces in the main urban area, we determine $d = 0.4$, $e = 0.5$, and $f = 0.7$. The resulting function is as follows:

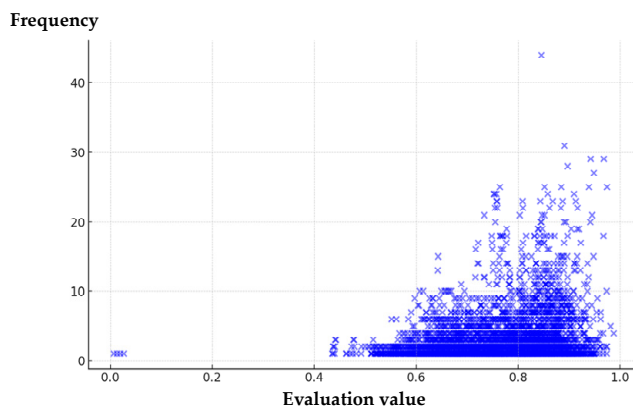
$$Y(X) = \begin{cases} 0.25 \ln \frac{0.25}{x_i} + 0.75, & x_i \in (0, 0.25) \\ 0.9 - x_i, & x_i \in (0.25, 0.5) \\ 2.5x_i^2 - 3x_i + 1.3, & x_i \in (0.5, 0.75) \\ 0.4, & x_i \in (0.75, 1) \end{cases} \quad (3)$$

Utilizing the variable weight theory along with W^0 and $Y(X)$, we derive the variable weightings for each evaluation indicator within the fundamental evaluation units. Given the considerable computational complexity involving matrix operations, this necessitates the use of MATLAB R2023b programming to facilitate implementation. The output results are presented in Table 3 below.

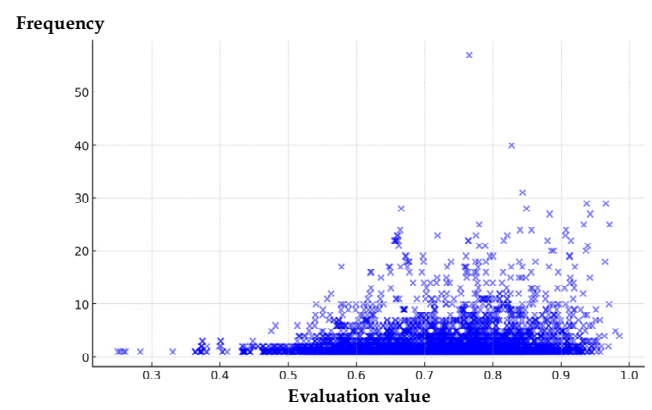
The indicator weights obtained using both the variable-weight hierarchical analysis method and the traditional hierarchical analysis method are summarized, and preliminary evaluation scores are calculated. Figures 6 and 7 depict scatter plots showing the evaluation scores for shallow underground spaces in the research area, generated using the multi-objective linear weighting method. The horizontal axis indicates the magnitude of the evaluation scores, while the vertical axis represents the frequency of occurrence for each score. Table 4 provides a comparative overview of the weighting results derived from the two variable-weight hierarchical analysis methods and the traditional method.

Table 3. Weighting results of the Analytic Hierarchy Process with variable weights for evaluation units.

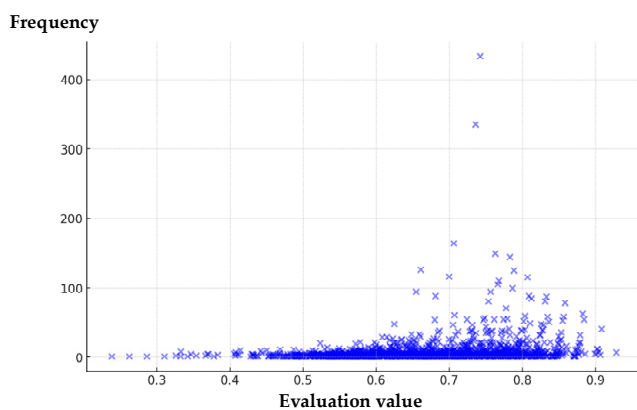
Evaluation Unit	1	2	3	.....	12,949	12,950	12,951
Population density	0.029	0.018	0.041	.....	0.027	0.029	0.028
Transportation accessibility	0.116	0.064	0.164	.....	0.096	1.000	0.090
Commercial land price	0.038	0.032	0.047	.....	0.084	0.057	0.045
Elevation	0.020	0.019	0.016	.....	0.016	0.017	0.016
Slope	0.004	0.004	0.003	.....	0.003	0.003	0.003
Topographic features	0.030	0.029	0.028	.....	0.025	0.030	0.027
Hydrophilicity	0.027	0.026	0.022	.....	0.023	0.024	0.021
Surface water system	0.055	0.052	0.044	.....	0.045	0.047	0.074
Existing buildings	0.132	0.127	0.107	.....	0.109	0.130	0.117
Soft soil layer thickness	0.274	0.263	0.221	.....	0.258	0.236	0.213
Rock and soil type	0.137	0.131	0.110	.....	0.113	0.118	0.106
Active fracture	0.070	0.117	0.099	.....	0.101	0.105	0.167
Disasters such as landslides and collapses	0.070	0.117	0.099	.....	0.101	0.105	0.095



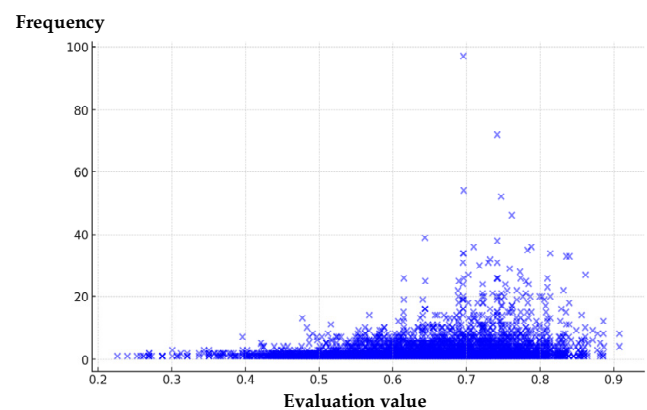
(a)



(b)

Figure 6. Comparison of weighting methods for shallow underground spaces: (a) score of Analytic Hierarchy Process; (b) score of Variable-Weight Analytic Hierarchy Process.

(a)



(b)

Figure 7. Comparison of weighting methods for medium and deep underground spaces: (a) score of Analytic Hierarchy Process; (b) score of Variable-Weight Analytic Hierarchy Process.

Table 4. Comparison table of results for different weighting methods.

Evaluation Depth	Weight Assignment Method							
	Analytic Hierarchy Process				Analytic Hierarchy Process with Variable Weights			
	Min	Max	Avg	SD	Min	Max	Avg	SD
Shallow layer	0.256	0.987	0.789	0.096	0.245	0.965	0.738	0.098
Middle to deep layers	0.238	0.929	0.718	0.093	0.226	0.907	0.678	0.097

From the graph, it can be observed that the comprehensive scores of shallow underground spaces obtained using the hierarchical analysis method mainly range from 0.6 to 0.95, with the overall center of gravity leaning towards the high-score region. The majority of the area falls within the high-score range, indicating a relatively concentrated distribution of evaluation results. In contrast, the distribution of comprehensive scores for shallow underground spaces obtained using the variable-weight hierarchical analysis method ranges from 0.5 to 0.9. According to the data in Table 3, it can be noted that the standard deviation is slightly higher compared to the former method. This suggests an increased dispersion of data points around the mean and a tendency towards a normal distribution, making the evaluation results more persuasive.

Due to the punitive nature of the variable-weight status function being greater than the incentive, the minimum, maximum, and average scores obtained from the variable-weight hierarchical analysis method have all decreased. The number of areas in the high-score region has decreased, while the number of areas in the medium-to-low-score region has significantly increased. This indicates that some areas where high-scoring factors coexist with low-scoring factors were classified as high-score regions when using the hierarchical analysis method. However, after adjusting their weights, they became medium-to-low-score regions, thereby reducing the likelihood of neutralization effects. Similarly, the comparison of comprehensive scores for the medium-to-deep underground spaces also exhibits similar characteristics. Through the comparison results mentioned above, it can be seen that the improvement in the hierarchical analysis method has led to evaluation results that are closer to the actual situation, providing better decision-making solutions for urban underground space development.

4. Comprehensive Evaluation Model

Currently, mathematical models used for multidimensional decision-making objectives include multi-objective linear weighted function models, fuzzy comprehensive evaluation models, grey system theory models, principal component analysis models, and other methods [35]. Each of these methods has its own advantages and disadvantages. Considering the experimental background and data collection circumstances, this paper opts to utilize two models—the multi-objective linear weighted function model and the fuzzy comprehensive evaluation model—as the comprehensive approaches for suitability assessment.

4.1. Multi-Objective Linear Function Weighted Model

The multi-objective linear weighted function method is an approach to solving multi-objective optimization problems. Its basic principle involves transforming multiple objectives into a single comprehensive objective function by assigning different weights, thereby enabling the evaluation and ranking of decision alternatives. This method balances and integrates multiple objectives through linear combinations, aiming to optimize the comprehensive evaluation value. The specific construction process is as follows:

1. **Objective Function Determination:** Suppose there are n decision alternatives, each with corresponding evaluation values for m objectives. Let f_{ij} represent the evaluation value of the i -th decision alternative on the j -th objective, where $i = 1, 2, 3, \dots, n$ and $j = 1, 2, 3, \dots, m$. In this experiment, $n = 13$ and $m = 1$.

2. **Weight Assignment:** Weight assignment is the essence of the multi-objective linear function weighting method. In this study, the Variable-Weighted Analytical Hierarchy Process (AHP) method, which yielded superior results after comparison, was adopted for weight assignment in the model. Additionally, the weights were standardized to ensure that the sum of all weights equals 1, represented as $\sum_{j=1}^m w_j = 1$, thereby ensuring the rationality and comparability of the weights.
3. **Constructing the Weighted Composite Objective Function:** For the i -th solution, its weighted composite objective function is defined as: $F_i = \sum_{j=1}^m w_j \cdot f_{ij}$, where f_{ij} represents the rating value of the i -th decision solution on the j -th objective, and w_j denotes the weight of the j -th objective.

4.2. Fuzzy Comprehensive Evaluation Model

Fuzzy comprehensive evaluation is a comprehensive assessment method grounded in fuzzy mathematics that is primarily used to address decision-making problems with uncertainty and strong fuzziness in evaluation factors. This method can effectively handle evaluation issues that combine qualitative and quantitative aspects, particularly suitable for complex system evaluations that are challenging to describe using precise mathematical models. Its core principle involves synthesizing fuzzy relations to combine multiple factors or evaluation criteria influencing the evaluation object. Through fuzzy transformation, these factors are integrated into a fuzzy set, reflecting the overall evaluation level of the evaluation object. The specific construction process is as follows:

1. **Determine the factor set:** Based on the constructed evaluation system, the secondary evaluation indicators in the system are taken as the factor set. $U = \{\text{Terrain and landforms, Geotechnical engineering geology, Hydrogeology, Adverse geological effects and disasters, Existing construction conditions, Urban planning requirements}\}$.
2. **The evaluation set is established according to the specific circumstances of each criterion or indicator, and in this experiment, the suitability evaluation is divided into four levels.** Therefore, the constructed evaluation set is $V = \{\text{Highly Suitable for Development, Moderately Suitable for Development, Marginally Suitable for Development, Not Suitable for Development}\}$.
3. **Weight Allocation:** Based on the importance of each criterion, assign a weight to each criterion or indicator, forming a weight set $W = \{w_1, w_2, \dots, w_n\}$, where $w_i (i = 1, 2, \dots, n)$ represents the weight value of the i -th evaluation criterion. The specific weight values have been obtained in the previous chapter.
4. **Membership Function Construction:** Membership functions are one of the core tools in fuzzy comprehensive evaluation, used to convert qualitative evaluations into quantitative values. The construction process of membership functions involves transforming actual evaluation data into membership degrees ranging from 0 to 1. In this study, trapezoidal membership functions are selected for calculating membership degrees. The specific functional expression is as follows:

$$y_1 = \begin{cases} 1 & x \leq 0.2 \\ 3 - 10x & 0.2 < x \leq 0.3 \\ 0 & x > 0.3 \end{cases} \quad (4)$$

$$y_2 = \begin{cases} 0 & x \leq 0.2 \\ 10x - 2 & 0.2 < x \leq 0.3 \\ 1 & 0.3 < x \leq 0.5 \\ 6 - 10x & 0.5 < x \leq 0.6 \\ 0 & x > 0.6 \end{cases} \quad (5)$$

$$y_3 = \begin{cases} 0 & x \leq 0.5 \\ 10x - 5 & 0.5 < x \leq 0.6 \\ 1 & 0.6 < x \leq 0.8 \\ 9 - 10x & 0.8 < x \leq 0.9 \\ 0 & x > 0.9 \end{cases} \quad (6)$$

$$y_4 = \begin{cases} 0 & x \leq 0.8 \\ 10x - 8 & 0.8 < x \leq 0.9 \\ 1 & x > 0.9 \end{cases} \quad (7)$$

In the equation, x represents the standardized value of the influencing factor, and y_1, y_2, y_3 , and y_4 represent the four levels of suitability development evaluation results: “Not Suitable for Development”, “Marginally Suitable for Development”, “Moderately Suitable for Development”, and “Highly Suitable for Development”, respectively. Based on this membership degree function, the membership degree set for each evaluation indicator can be calculated.

5. The fuzzy matrix R is a matrix representing the fuzzy relationships between the factor set $U_i (i = 1, 2, \dots, n)$ and the evaluation set $V_j (j = 1, 2, \dots, m)$. The fuzzy matrix R is an $n \times m$ matrix, where n represents the number of evaluation indicators and m represents the number of evaluation levels. Taking shallow underground space evaluation as an example, there are a total of 13 evaluation indicators, so $n = 13$, and there are four evaluation levels, so $m = 4$. The element r_{ij} in the fuzzy matrix R ($n \times m$) represents the degree of membership of the i -th evaluation indicator to the j -th evaluation level.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \quad (8)$$

6. Fuzzy Comprehensive Evaluation: To obtain the final evaluation result, it is necessary to perform fuzzy synthesis operation on the weight vector W and the fuzzy relationship matrix R . The comprehensive evaluation result B is calculated as $B = W \cdot R$, where the fuzzy synthesis operation used is the weighted averaging method. That is:

$$B = (w_1, w_2, \dots, w_n) \cdot \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} = (b_1, b_2, \dots, b_m) \quad (9)$$

where B represents the fuzzy evaluation result set. Finally, de-fuzzification is performed to convert B into explicit evaluation grades. This process can be accomplished using either the maximum membership principle method or the weighted evaluation method.

5. Results

5.1. Comparative Analysis of Suitability Evaluation Results

After spatial overlay analysis, a total of 12,951 new vector units were generated as the final minimum evaluation units for comprehensive assessment. Each vector unit contains scores for various evaluation indicators, along with their corresponding weights. These units were utilized for assessing the suitability of urban underground space development within the study area using the two aforementioned models. Figure 8 displays the data for each evaluation indicator used in the overlay process, while Figures 9 and 10 depict the

suitability results obtained using the two models. Table 5 presents the statistical results of suitability zoning.

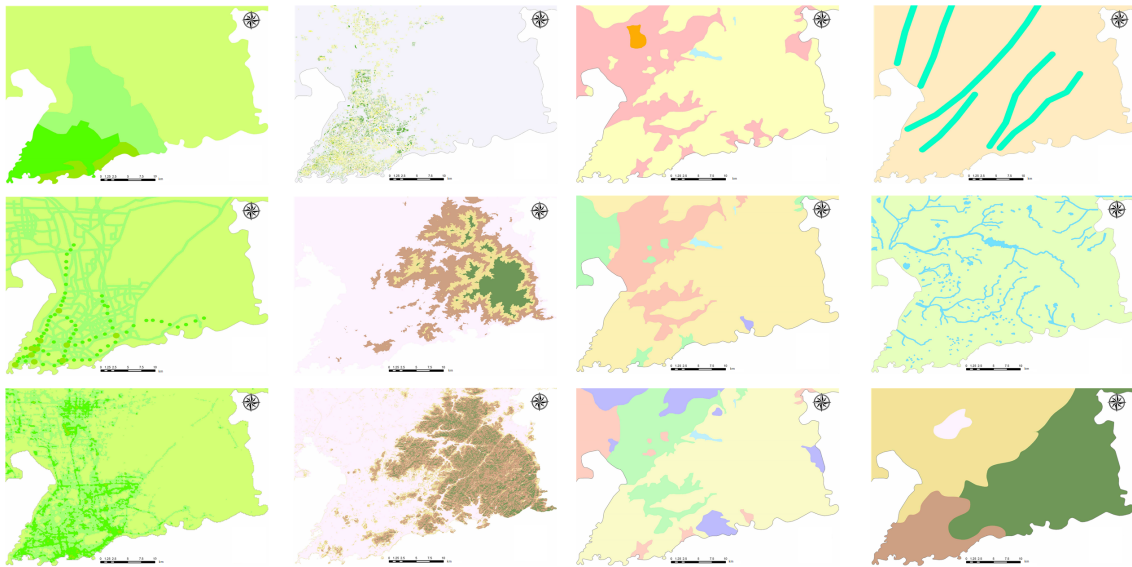


Figure 8. Grading score chart of various evaluation indicators.

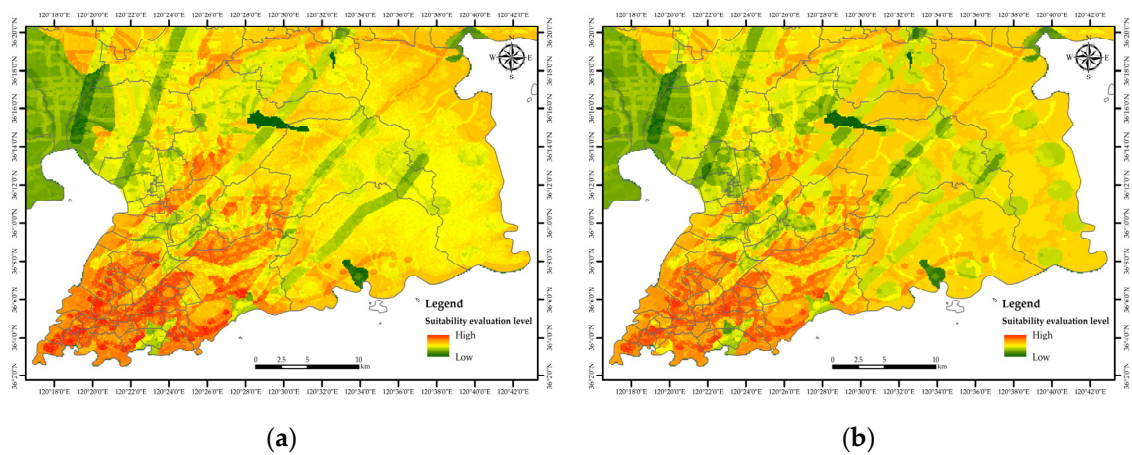


Figure 9. Results of suitability evaluation for shallow underground spaces: (a) multi-objective linear function weighted model; (b) fuzzy comprehensive evaluation model.

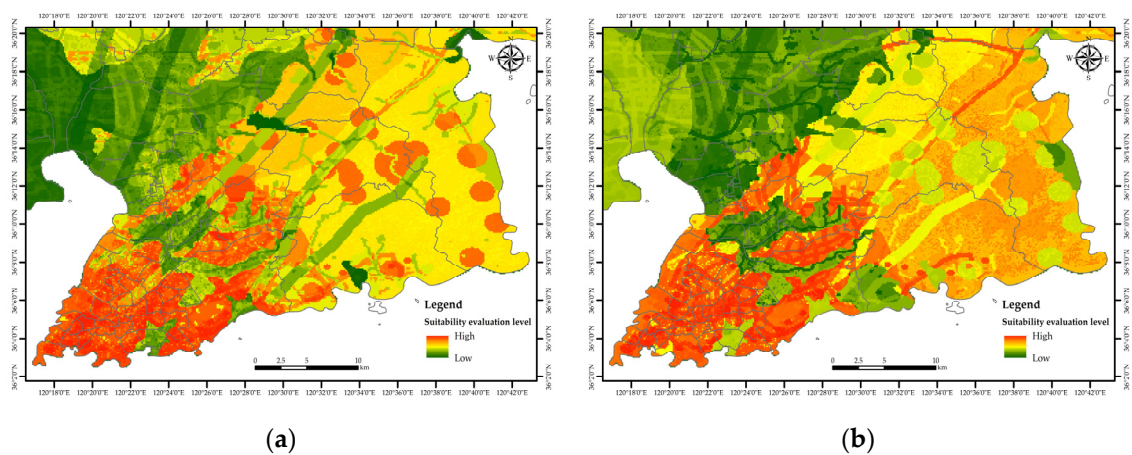


Figure 10. Results of suitability evaluation for medium and deep underground spaces: (a) multi-objective linear function weighted model; (b) fuzzy comprehensive evaluation model.

Table 5. Statistical table of suitability evaluation results for comprehensive evaluation models.

Evaluation Depth	Suitability Level	Comprehensive Evaluation Model			
		Multi-Objective Linear Function Weighted Model		Fuzzy Comprehensive Evaluation Model	
		Square Measure (km ²)	Proportion (%)	Square Measure (km ²)	Proportion (%)
Shallow layer	Very suitable	69.42	7.18	47.59	4.92
	More suitable	429.01	44.35	62.96	6.51
	Generally suitable	363.74	37.60	531.63	54.96
	Not suitable	105.16	10.87	325.15	33.61
Middle to deep layers	Very suitable	46.34	4.79	50.71	5.24
	More suitable	96.73	10.00	55.98	5.79
	Generally suitable	220.88	22.83	478.99	49.52
	Not suitable	603.38	62.38	381.64	39.45

From the table and the graphs, it is evident that both models demonstrate good practicality and feasibility in real-world applications. However, the fuzzy comprehensive evaluation model tends to classify parcels more towards moderately suitable and unsuitable for development. The application of the fuzzy comprehensive evaluation model reduces reliance on subjective judgment in the assessment process by quantifying and managing the uncertainty of evaluation factors using fuzzy mathematics. This approach enhances the objectivity and scientific rigor of the evaluation process, providing more forward-looking and cautionary evaluation results for urban planning and development. Therefore, this model exhibits more advantages in assessing the suitability of urban underground space development.

5.2. Distribution of Suitability Level Zoning

By employing both the fuzzy comprehensive evaluation model and the variable-weight analytic hierarchy process, the study obtained the final assessment outcomes regarding the suitability of urban underground space development in Qingdao City's main urban area. The study area encompasses regions within the districts of Shinan, Shibei, Laoshan, and Licang and parts of Chengyang. The suitability zoning evaluation results obtained through the fuzzy comprehensive evaluation model exhibit significant distribution characteristics within each administrative district. The areas of different suitability levels within the main urban area, along with their proportional areas within their respective administrative districts, are illustrated in Figure 11.

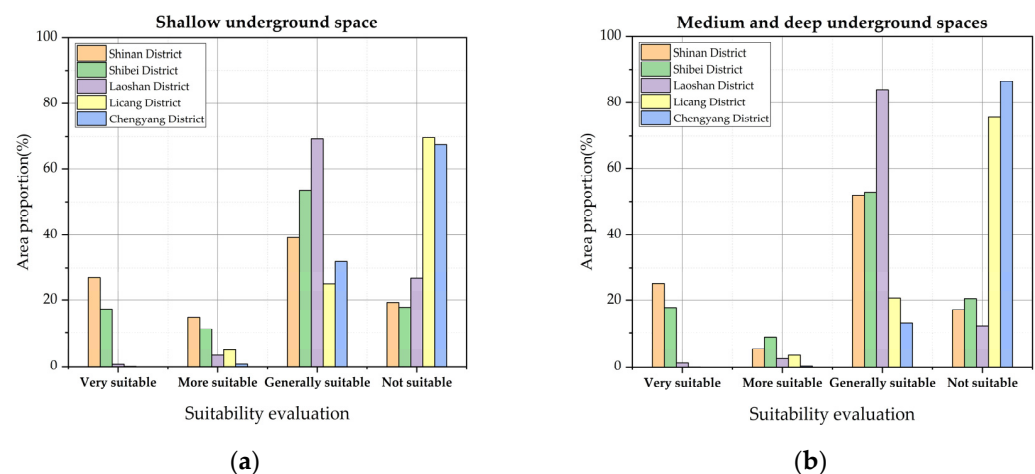


Figure 11. The proportion of evaluation levels in each administrative region: (a) distribution of shallow underground space; (b) distribution of medium and deep underground spaces.

Figures 12 and 13 depict the evaluation outcomes concerning the suitability of utilizing shallow and medium–deep underground space development in the main urban area of Qingdao City. Green areas indicate regions unsuitable or generally suitable for underground space development utilization, while yellow and orange areas signify areas comparatively suitable or highly suitable for underground space development utilization, respectively.

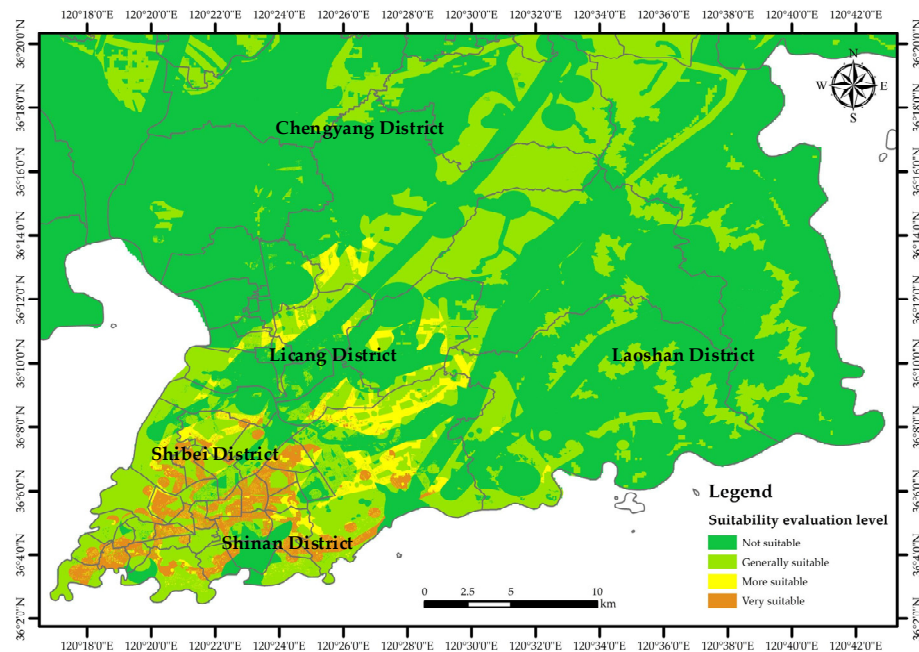


Figure 12. Results of suitability evaluation for the development and utilization of shallow underground spaces in the main urban area of Qingdao City.

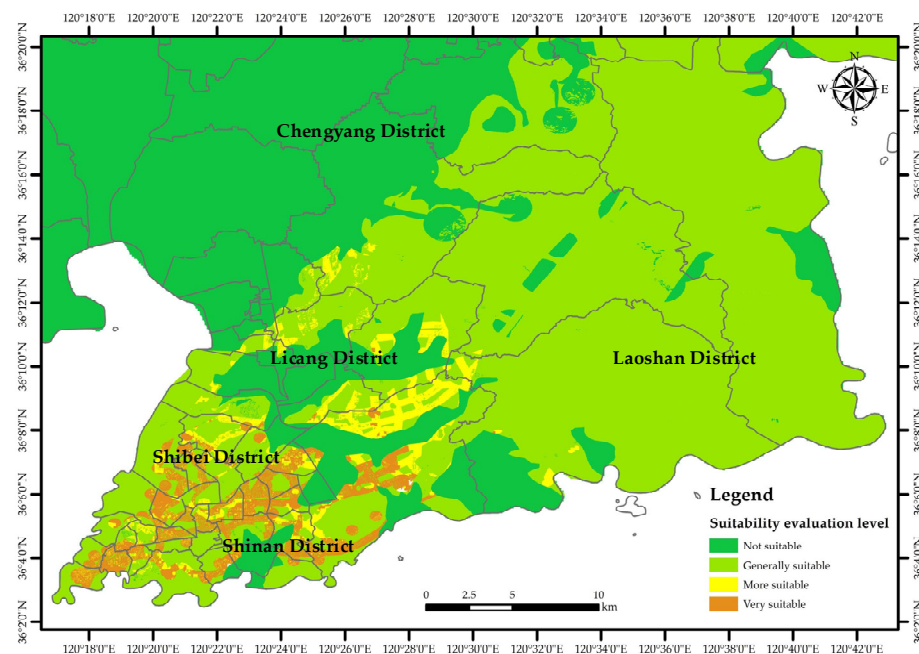


Figure 13. Results of suitability evaluation for the development and utilization of medium and deep underground spaces in the main urban area of Qingdao City.

From Table 6, it can be observed that areas rated as “Highly Suitable” are concentrated in the southern and northern districts of the research area. There are few areas in Laoshan

District that are highly suitable for development, while Licang District and Chengyang District have virtually no areas rated as highly suitable. Specifically, the combined area of highly suitable and moderately suitable development zones in the southern district exceeds 40% of the total area, and in the northern district, it reaches nearly 30%, significantly higher than the other three districts. Therefore, the southern and northern districts are the key areas for the current development and utilization of shallow underground spaces in the main urban area of Qingdao.

Table 6. Distribution of suitability evaluation levels for shallow underground spaces in the main urban area.

Administrative Region	Suitability Level	Square Measure (km ²)	Proportion (%)
Shinan District	Very suitable	14.22	26.85
	More suitable	7.77	14.67
	Generally suitable	20.74	39.15
	Not suitable	10.24	19.33
Shibei District	Very suitable	12.29	17.33
	More suitable	7.92	11.17
	Generally suitable	38.02	53.62
	Not suitable	12.67	17.87
Laoshan District	Very suitable	3.75	0.81
	More suitable	15.88	3.43
	Generally suitable	319.28	69.04
	Not suitable	123.49	26.70
Licang District	Very suitable	0.19	0.13
	More suitable	7.63	5.04
	Generally suitable	37.96	25.09
	Not suitable	105.42	69.69
Chengyang District	Very suitable	0	0
	More suitable	1.91	0.85
	Generally suitable	71.45	31.83
	Not suitable	151.08	67.31

Table 7 presents the distribution of suitability evaluation levels for medium and deep underground spaces within the research area. It can be observed that areas with favorable suitability evaluation results are still predominantly concentrated in the southern and northern districts. Their respective proportions of the district area exceed 30% and 25%. In Laoshan District, over 80% of the area is rated as moderately suitable for development, while in Licang District and Chengyang District, 75.76% and 86.45% of the areas, respectively, are deemed unsuitable for underground space development. Therefore, the focus of underground space development across various depth levels within the research area remains centered on specific areas within the southern and northern districts, as well as select areas within Laoshan and Licang districts. When formulating specific development and utilization plans for the main urban area of Qingdao, emphasis should be placed on these key development zones.

Table 7. Distribution of suitability evaluation levels for medium and deep underground spaces in the main urban area.

Administrative Region	Suitability Level	Square Measure (km ²)	Proportion (%)
Shinan District	Very suitable	13.34	25.18
	More suitable	2.92	5.51
	Generally suitable	27.6	52.1
	Not suitable	9.11	17.2
Shibei District	Very suitable	12.66	17.85
	More suitable	6.23	8.79
	Generally suitable	37.54	52.94
	Not suitable	14.48	20.42
Laoshan District	Very suitable	6.12	1.32
	More suitable	11.85	2.56
	Generally suitable	387.69	83.84
	Not suitable	56.74	12.27
Licang District	Very suitable	0.12	0.08
	More suitable	5.38	3.56
	Generally suitable	31.16	20.61
	Not suitable	114.55	75.76
Chengyang District	Very suitable	0	0
	More suitable	0.83	0.37
	Generally suitable	29.59	13.18
	Not suitable	194.04	86.45

6. Conclusions

1. After analyzing six influencing factors, including topography, engineering geological conditions, adverse geological effects and faults, hydrogeology, existing construction conditions, and urban planning requirements, thirteen impact factors were selected as evaluation indicators in the assessment system. These factors include surface elevation, terrain type, surface slope, geological formation type, thickness of soft soil, surface water, aquifer characteristics, landslide and collapse, active faults, depth of building influence, transportation accessibility, population density, and commercial land prices.
2. By introducing a local weighting function into the traditional Analytic Hierarchy Process (AHP), the Variable-Weight Analytic Hierarchy Process (VWAHP) method is obtained. This method allows for timely adjustments of weights based on the characteristics of the evaluation areas when assigning weights to evaluation criteria. A comparison of the weighting results between the two methods reveals that VWAHP can effectively reduce the occurrence of “neutralization effects” during the evaluation process. Therefore, in subsequent comprehensive evaluation models, the weight results obtained from VWAHP are used as the weight set in the model.
3. Using both the multi-objective linear weighting function model and the fuzzy comprehensive evaluation model for the suitability assessment of Qingdao’s main urban area, a comparison of the evaluation results from the two models reveals that the fuzzy comprehensive evaluation model tends to be more conservative in delineating areas classified as “highly suitable” and “moderately suitable”. Compared to the multi-objective linear weighting function model, the fuzzy comprehensive evaluation model provides more forward-looking and cautionary evaluation results for the development and utilization of urban underground spaces.
4. The evaluation results obtained using the fuzzy comprehensive evaluation model indicate that areas with higher evaluation grades are primarily concentrated in the districts of Shinan and Shibei, as well as in the Xinghua Road and Yong’an Road streets in Licang District. These areas possess favorable geological and hydrological conditions, along with relatively high economic development benefits. Conversely, lower

evaluation grades in most areas of Laoshan and Chengyang districts are attributed to poor engineering geological conditions or lower urban planning demands, resulting in lower evaluation scores. When planning for the development and utilization of underground spaces, areas with higher suitability evaluation grades are designated as priority development zones.

5. In this study, engineering geological conditions of the underground and the urban planning demand conditions above ground were mainly used. The functional data of urban underground space development and the existing underground structure data can be used to further improve the evaluation results in such research in the future.

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References

1. Broere, W. Urban underground space: Solving the problems of today's cities. *Tunn. Undergr. Space Technol.* **2016**, *55*, 245–248. [\[CrossRef\]](#)
2. Nelson, P.P. A framework for the future of urban underground engineering. *Tunn. Undergr. Space Technol.* **2016**, *55*, 32–39. [\[CrossRef\]](#)
3. Zhu, H.; Huang, X.; Li, X.; Zhang, L.; Liu, X. Evaluation of urban underground space resources using digitalization technologies. *Undergr. Space.* **2016**, *1*, 124–136. [\[CrossRef\]](#)
4. Wang, X.; Zhen, F.; Huang, X. Factors influencing the development potential of urban underground space: Structural equation model approach. *Tunn. Undergr. Space Technol.* **2013**, *38*, 235–243. [\[CrossRef\]](#)
5. Hou, W.; Yang, L.; Deng, D. Assessing quality of urban underground spaces by coupling 3D geological models: The case study of Foshan city South China. *Comput. Geosci.* **2016**, *89*, 1–11. [\[CrossRef\]](#)
6. Tan, F.; Wang, J.; Jiao, Y.Y. Suitability evaluation of underground space based on finite interval cloud model and genetic algorithm combination weighting. *Tunn. Undergr. Space Technol.* **2020**, *108*, 103743. [\[CrossRef\]](#)
7. Sterling, R.L. Cost and code study of underground building: A report to the Minnesota Energy Agency. *Undergr. Space.* **1979**, *4*, 119–136.
8. Rönkä, K.; Ritola, J.; Rauhala, K. Underground space in land-use planning. *Tunn. Undergr. Space Technol.* **1998**, *13*, 39–49. [\[CrossRef\]](#)
9. Boivin, D.J. Underground space use and planning in the Quebec City area. *Tunn. Undergr. Space Technol.* **1990**, *5*, 69–83. [\[CrossRef\]](#)
10. De Rienzo, F.; Oreste, P.; Pelizza, S. 3D GIS supporting underground urbanisation in the city of Turin (Italy). *Geotech. Geol. Eng.* **2009**, *27*, 539–547. [\[CrossRef\]](#)
11. Wang, Y.; Peng, F. Evaluation of urban underground space based on the geological conditions: A feasibility study. In *New Frontiers in Geotechnical Engineering*; Springer: Singapore, 2014; pp. 187–197.
12. Qiao, Y.; Peng, F.; Wang, Y. Monetary valuation of urban underground space: A critical issue for the decision-making of urban underground space development. *Land Use Policy* **2017**, *69*, 12–24. [\[CrossRef\]](#)
13. Li, X.; Li, C.; Parriaux, A. Multiple resources and their sustainable development in Urban Underground Space. *Tunn. Undergr. Space Technol.* **2016**, *55*, 59–66. [\[CrossRef\]](#)
14. Zaini, F.; Hussin, K.; Raid, M.M. Legal considerations for urban underground space development in Malaysia. *Undergr. Space* **2017**, *2*, 234–245. [\[CrossRef\]](#)

15. Tengborg, P.; Sturk, R. Development of the use of underground space in Sweden. *Tunn. Undergr. Space Technol.* **2016**, *55*, 339–341. [[CrossRef](#)]
16. Bobylev, N. Mainstreaming sustainable development into a city's Master plan: A case of Urban Underground Space use. *Land Use Policy* **2009**, *26*, 1128–1137. [[CrossRef](#)]
17. He, L.; Song, Y.; Dai, S. Quantitative research on the capacity of urban underground space—The case of Shanghai, China. *Tunn. Undergr. Space Technol.* **2012**, *32*, 168–179. [[CrossRef](#)]
18. Liu, Y.F.; Song, Z.Q.; Sun, H.L. Analysis of the influence of economic factors on the development and utilization of underground space in the city center. *Appl. Mech. Mater.* **2014**, *584*, 2404–2410. [[CrossRef](#)]
19. Peng, Z.; Zhang, Y.; Tan, F. Variable-weight suitability evaluation of underground space development considering socioeconomic factors. *Sustainability* **2023**, *15*, 3574. [[CrossRef](#)]
20. Youssef, A.M.; Biswajeet, P.; Abdallah, M.H. Flash flood risk estimation along the St. Katherine road, southern Sinai, Egypt using GIS based morphometry and satellite imagery. *Environ. Earth Sci.* **2011**, *62*, 611–623. [[CrossRef](#)]
21. Durmisevic, S.; Sariyildiz, S. A systematic quality assessment of underground spaces—public transport stations. *Cities* **2001**, *18*, 13–23. [[CrossRef](#)]
22. Dou, F.; Xing, H.; Li, X. 3D Geological Suitability Evaluation for Urban Underground Space Development Based on Combined Weighting and Improved TOPSI. *Nat. Resour. Res.* **2022**, *31*, 693–711. [[CrossRef](#)]
23. Li, H.Q.; Parriaux, A.; Thalmann, P.; Li, X.Z. An integrated planning concept for the emerging underground urbanism: Deep City Method Part 1 concept, process and application. *Tunn. Undergr. Space Technol.* **2013**, *38*, 559–568. [[CrossRef](#)]
24. Peng, J.; Peng, F.L. A GIS-based evaluation method of underground space resources for urban spatial planning: Part 1 methodology. *Tunn. Undergr. Space Technol.* **2018**, *74*, 82–95. [[CrossRef](#)]
25. Zhou, D.; Li, X.; Wang, Q. GIS-based urban underground space resources evaluation toward three-dimensional land planning: A case study in Nantong, China. *Tunn. Undergr. Space Technol.* **2019**, *84*, 1–10. [[CrossRef](#)]
26. Zhang, Y.; Zhu, J.; Liao, Z. An intelligent planning model for the development and utilization of urban underground space with an application to the Luohu District in Shenzhen. *Tunn. Undergr. Space Technol.* **2021**, *112*, 103933. [[CrossRef](#)]
27. Xu, Z.; Zhou, S.; Zhang, C. A Bayesian network model for suitability evaluation of underground space development in urban areas: The case of Changsha, China. *J. Clean Prod.* **2023**, *418*, 138135. [[CrossRef](#)]
28. Dou, F.; Li, X.; Xing, H. 3D geological suitability evaluation for urban underground space development—A case study of Qianjiang Newtown in Hangzhou, Eastern China. *Tunn. Undergr. Space Technol.* **2021**, *115*, 104052. [[CrossRef](#)]
29. Mavrikos, A.; Kaliampakos, D. An integrated methodology for estimating the value of underground space. *Tunn. Undergr. Space Technol.* **2021**, *109*, 103770. [[CrossRef](#)]
30. Yu, P.; Liu, H.; Wang, Z. Development of urban underground space in coastal cities in China: A review. *Deep Undergr. Sci. Eng.* **2023**, *2*, 148–172. [[CrossRef](#)]
31. Rodríguez-Pérez, Á.M.; Rodríguez, C.A.; Márquez-Rodríguez, A.; Mancera, J.J.C. Viability Analysis of Tidal Turbine Installation Using Fuzzy Logic: Case Study and Design Considerations. *Axioms* **2023**, *12*, 778. [[CrossRef](#)]
32. Li, X.; Lei, L.; Li, J. Integrating ecosystem service value into the evaluation of sustainable land use in fast-growing cities: A case study of Qingdao, China. *Ecol. Indic.* **2023**, *153*, 110434. [[CrossRef](#)]
33. Podvezko, V. Application of AHP technique. *J. Bus. Econ. Manag.* **2009**, *2*, 181–189. [[CrossRef](#)]
34. Wang, P.Z.; Zhang, H.M. Truth-Valued Flow Inference and its Mathematical Theory. In *Between Mind and Computer: Fuzzy Science and Engineering*; World Scientific: Singapore, 1993; pp. 325–358.
35. Liang, Z.H.; Yang, K.; Sun, Y.W.; Yuan, J.H.; Zhang, H.W.; Zhang, Z.Z. Decision support for choice optimal power generation projects: Fuzzy comprehensive evaluation model based on the electricity market. *Energy Policy* **2006**, *34*, 3359–3364. [[CrossRef](#)]

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