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A FOUR-STAGE SUITABILITY EVALUATION FRAMEWORK CONSIDERING RESTRICTIVE FACTOR FOR UNDERGROUND SPACE SUSTAINABLE DEVELOPMENT AND THE APPLICATION IN JINAN PILOT ZONE

Un marco de evaluación de la idoneidad en cuatro etapas que considere un factor restrictivo para el desarrollo sostenible del espacio subterráneo y su aplicación en la zona piloto de Jinan

Quanlin FENG[1,2,3], Hongjie SUN[1,2,3], Yang WANG[1,2,3],
Zhenhua ZHAO[1,2,3], Kai LIU[4]*, Zhihui WANG[4] and Jinkai YAN[4]

[1] 801 Institute of Hydrogeology and Engineering Geology, Shandong Provincial Bureau of Geology & Mineral Resources, Jinan, Shandong 250014, China.
[2] Key Laboratory of Groundwater Resources and Environment, Shandong Provincial Bureau of Geology & Mineral Resources, Jinan 250014, China.
[3] Shandong Engineering Research Center for Environmental Protection and Remediation on Groundwater, Jinan, Shandong 250014, China.
[4] Chinese Academy of Geological Sciences, Beijing 100037, China.

*Author for correspondence: chaobin_in@163.com

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ABSTRACT

One of the primary concerns for sustainable and safety development of urban underground space is to find out the key restrictive factors and the corresponding methods to avoid or modify the constraints. Aiming to provide practical decisions, a four-stage evaluation framework with fuzzy mathematics comprehensive evaluation (FMCE) method was adapted and proposed considering the restrictive factors and management programs. The four stages are 1) identifying the major indicators and restrictive factors that represent geological conditions, 2) collecting data from literature, field investigation and experts' judgements, 3) combing the qualitative information and quantitative calculation to evaluate the suitability, 4) providing feasible suggestions with management programs that weaken the disadvantage. The four-stage framework is applied in Jinan Pilot Zone as an example. The FMCE method is conducted by employing hydrology, hydrogeology, engineering geology, mining goaf (the restrictive factor), building foundation, and developed underground space as the primary evaluation factors. Protected areas are indicated and two schemes of recharge filling and secondary landscape development are compared in terms of costs and benefits. It is suggested that the existing facilities should be used to develop the underground space with exploration and tourism projects, which might become one highlight of the Pilot Zone.

Palabras clave: espacio subterráneo, factores restrictivos, evaluación comprensiva con matemáticas difusas, residuos mineros, zona piloto de Jinan

RESUMEN

Una de las principales preocupaciones para el desarrollo sostenible y de seguridad del espacio subterráneo urbano es descubrir los factores restrictivos clave y los métodos correspondientes para evitar o modificar las restricciones. Con el objetivo de proporcionar decisiones prácticas, se adaptó y propuso un marco de evaluación en cuatro etapas con un método de evaluación integral de matemáticas difusas (FMCE), considerando los factores restrictivos y los programas de gestión. Las cuatro etapas son 1) la identificación de los principales indicadores y factores restrictivos que representan las condiciones geológicas, 2) la recopilación de datos de la literatura, la investigación sobre el terreno y los juicios de expertos, 3) analizar la información cualitativa y el cálculo cuantitativo para evaluar la idoneidad, 4) proporcionar sugerencias viables con programas de gestión que disminuyan la desventaja. El marco de cuatro etapas se aplica en la zona piloto de Jinan como ejemplo. El método FMCE considera la hidrología, hidrogeología, la ingeniería geológica y los residuos mineros (el factor restrictivo), los cimientos de la construcción, y el espacio subterráneo desarrollado como los principales factores de evaluación. Se indican las áreas protegidas y se comparan dos esquemas de recarga y desarrollo secundario del paisaje en términos de costos y beneficios. Se sugiere que las instalaciones existentes se utilicen para desarrollar el espacio subterráneo con proyectos de exploración y turismo, que podrían convertirse en uno de los aspectos destacados de la Zona Piloto.

INTRODUCTION

There is an increasing demand for underground space for sustainable urban development considering the acceleration of urbanization (Qiao et al. 2019, Zhang 2019, TaRkowski and Uliasz-Misiak 2021). Underground space plays an important role in terms of urban structure optimization, land use efficiency improvement, traffic congestion alleviation, resilience enhancement (Admiraal and Cornaro 2020), and environmental protection (Broere 2016, Bidarmaghz et al. 2020). The design and utilization of underground space have been pointed out as an indispensable and viable solution for city planning and management (Price et al. 2016, Peng et al. 2020). For example, smart utility tunnels, cross-river tunnels, rail transit construction, and underground logistics are clearly stated as the main pattern for the development of the underground space in Jinan New and Old Growth Driver Conversion Pilot Zone (hereafter referred to as Pilot Zone) (2018-2035).

Unlike above-ground engineering projects, underground space development needs more investigation and evaluation due to its irreversibility and complex integration with above-ground structures (Sterling et al. 2012, Zhang et al. 2020). Geological environmental conditions (GEC) are a prerequisite for the safe and effective development of non-renewable underground space (Zhu et al. 2016, Yuan et al. 2019, Ku et al. 2020). Endowment resources assessment, key constraints identification, and suitability evaluation are beneficial to establish transparent, safe, three-dimensional, and efficient planning of underground space development and utilization (Lu et al. 2016, Chen et al. 2018, Zhou et al. 2019). According to experience from underground development projects, it is of great significance to evaluate the GEC and avoid or modify unfavorable GEC in order to improve sustainable underground space development (Pankratova et al. 2016, Wang et al. 2019, Xie et al. 2020).

Scientific and reasonable evaluation methods have been put forward to evaluate the suitability of underground space, such as Monte Carlo Method, GIS-based evaluation method, analytic hierarchy process (AHP) and the most unfavorable grading/rating method (Canto-Perello et al. 2013, Hyun et al. 2015, Zhu et al. 2016). The Monte Carlo Method is carried out with random numbers satisfying normal distribution characteristics to assess the safety performance of an underground cavern excavation (Guo et al. 2020). Peng and Peng (2018) conducted a relatively practicable index system for urban underground space resource evaluation with its analytical process based on the Geographic Information System (GIS). AHP (Saaty, 1980) is a useful method for solving multi-criteria problems illustrated with examples of practical decisions (Greco et al. 2016, Peng and Peng, 2018). Some studies have employed one-side techniques like AHP (for weighting the criteria subjectively) (Zhang et al. 2020). The most unfavorable grading method has been mentioned by Wang and Peng (2014) and Liu and Zhu (2004), while a few examples have been studied in regard to underground space evaluation. An integrated methodological approach for the appraisal of the underground space value is proposed combining established real estate appraisal techniques and environmental economics (Mavrikos and Kaliampakos, 2021). Urban underground planning and management have been also discussed with the systemic approaches (von der Tann et al. 2020).

However, the consideration and management of restrictive factors have not been carefully considered in previous studies. In terms of sustainable and safe development of urban underground space, the determination of key restrictive factors and the methods to avoid or modify the constraints due to geological conditions are critical. Little of the extant studies have considered the influence of restrictive factors on evaluation, and previous studies have taken almost no account of restrictive factor management program.

Compared with previous studies, an evaluation framework with a fuzzy mathematics comprehensive evaluation (FMCE) method (Zhou et al. 2019) was adapted with considering the restrictive factor and management programs to deal with the feasible support generated in realistic decisions. To illustrate the feasibility of the proposed framework, a detailed case study of Jinan Pilot Zone regarding the evaluation of the suitability of underground space development was conducted. Based on the geological survey of the Pilot Zone, the Jiyang coal mining goaf was determined to be the key restrictive factor in the development of the underground space. The first-level evaluation factor consisted of the hydrology, hydrogeology, engineering geology, mining goaf, and existing construction facilites. The results provide practical suggestions for the sustainable development and utilization of the underground space in the Pilot Zone.

FOUR-STAGE EVALUATION FRAMEWORK AND METHODS

A four-stage framework for underground space sustainable evaluation is proposed and modified based on literature reviews (Peng and Peng 2018, Wu and Hu 2020, Xu and Dong 2020), as shown in **figure 1.** The main task and the first step of the preparation of the suitability evaluation is to determine the key evaluation factors, criteria or indicators related to the GEC affecting the development of underground space. Hydrogeological conditions, engineering geological conditions, and existing facilities are the most approbative evaluation factors related to underground space development (Li et al. 2012, Wang and Peng 2014, Li et al. 2016, Peng and Peng 2018, Zhang et al. 2020). In other cases, regional geological conditions (Zhang et al. 2020) and topography and geomorphology (Li et al. 2016) are also listed as the first-level factors. Sub-factors or second-level factors rely heavily on the characteristics of the evaluation location. Normally, the source and level of groundwater, for example, are usually included in hydrogeological conditions. The characteristics of bedrock, weak interlayer and its thickness and heterogeneity, and bearing capacity of the foundations are common options in engineering geological conditions. Goaf collapse is recognized as a restrictive factor in regard to the evaluation of underground space development (Li et al. 2012).

The second step is to collect the data of the factors determined in the first step. In a comprehensive assessment system, both quantitative and qualitative criteria may be involved, where the data of the qualitative criteria are contributed by experts' descriptions, while that of the quantitative ones might be preliminarily collected from literature or calculated by specific simulation/software (Xu and Dong 2020). The main source is known as field investigation, which costs lots of time and money but is essential to the assessment.

Determining or grading the weight of the factor is a vital step for carrying out the suitability evaluation. Generally, the weight of a factor can be derived from different perspectives, and the most commonly employed way to determine the weight is by consulting insightful experts, the preferences of decision-makers, and the actual conditions of the investigated system by resorting to subjective weighting methods, like AHP. The process of AHP and EQS (Export Questionnaires Survey) have been described in detail in Li et al. (2012), Zhao et al. (2009), and Wu and Hu (2020). Meanwhile, other analysis approaches like DEMATEL (decision-making trial and evaluation laboratory) (Ren and Toniolo 2018), fuzzy BWM (best-worst method), CRITIC (criteria importance through intercriteria correlation), are also conducted in multi-level factor decision analysis (Xu and Dong 2020).

The last step is to perform the evaluation and propose management suggestions based on the evaluation results, especially considering the restrictive factor. The fuzzy mathematics comprehensive evaluation (FMCE) method (Zhou et al. 2019) is conducted to synthetically consider the factors that affect different levels of underground space development.

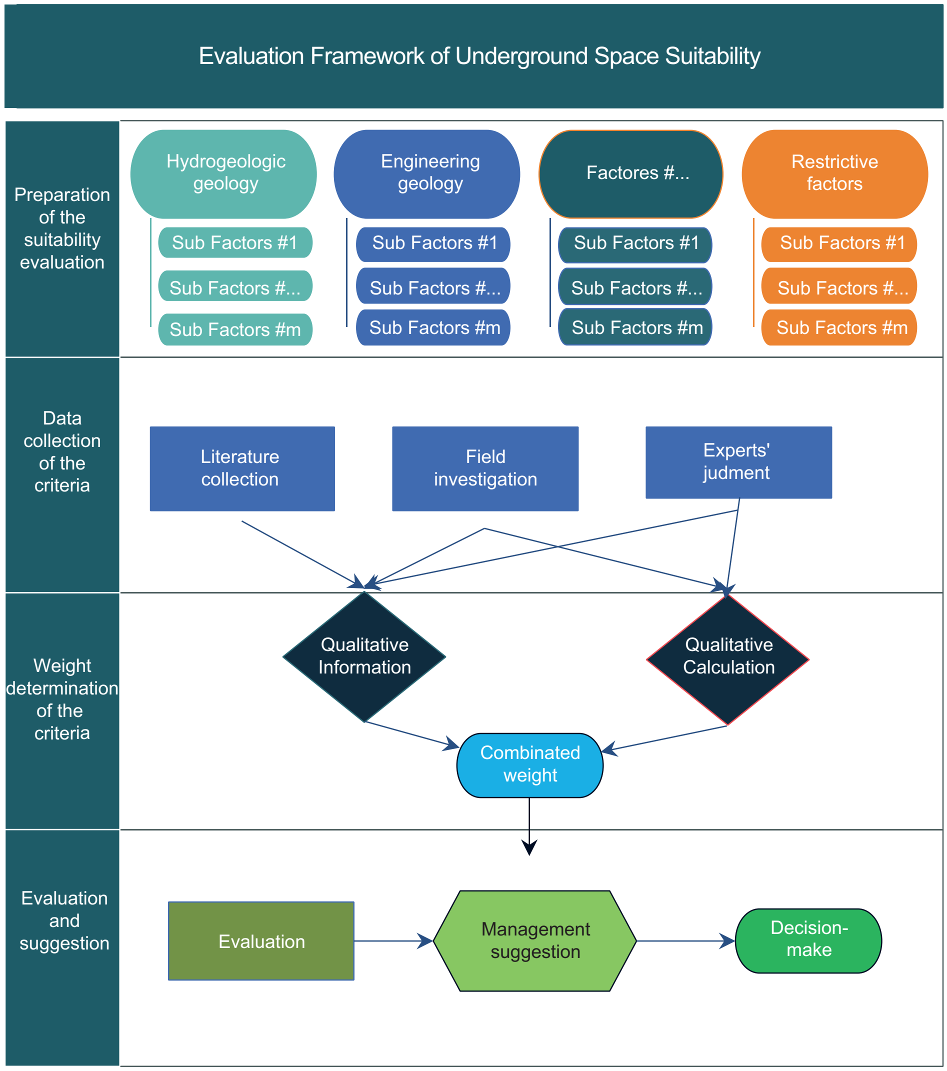

Fig. 1. Modified evaluation framework of underground space with restrictive factors.

The FMCE method has been used in many areas to evaluate the influence of multiple factors (Zhang et al. 2012). Afterward, the fuzzy matrix compound operation method is used to obtain comprehensive evaluation results. In the aspect of underground space geological suitability evaluation, the FMCE has been applied in Nanjing, Xi'an, Chongqing, and other cities (Peng et al. 2015, Yang 2016, Zhang 2016, Hong 2019). According to the principle of fuzzy set, the mathematical model of geological environment suitability by the FMCE is established as follows:

$$B = A \cdot R = [a_1 a_2 \cdots a_n] \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1m} \\ u_{21} & u_{22} & \cdots & u_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ u_{n1} & u_{n2} & \cdots & u_{nm} \end{bmatrix} = [b_1 b_2 \cdots b_m] \quad (1)$$

where A-weight matrix of factor set, a_i is the weight value obtained by the i-th evaluation index in the total target, and the sum is 1, R—the total evaluation matrix consisting of n evaluation factors, and u_{ij} is the membership degree of the i-th factor of the j-th program, B—Comprehensive evaluation matrix (comprehensive evaluation result), b_j is the comprehensive evaluation index of the j-th program.

A CASE STUDY OF THE SUITABILITY EVALUATION OF SHALLOW UNDERGROUND SPACE IN JINAN PILOT ZONE

A safe, three-dimensional, and efficient development and utilization plan for urban underground space is proposed for Jinan Pilot Zone. Compared with the Jinan central area, the geological conditions are relatively simple, the terrain is flat and the soil layer is thick. Another obvious advantage for sustainable development is that cold and hot spring resources are widely distributed in the Pilot Zone. In addition, the groundwater conditions are good for the protection of the spring. These features are conducive to the construction of engineering exploration and infrastructure projects, and can better facilitate the development of the concepts “green, smart, and modern” in the Pilot Zone.

Evaluation factor identification and data collection

A lot of researches on the influencing factors of urban underground space suitability are conducted by means of expert questionnaire survey and entropy weight method (Tan et al. 2021). Based on the four-stage evaluation framework, a comprehensive geological survey was carried out to find out the main evaluation factor. As mentioned in the previous section, the hydrogeology, engineering geology and building foundations and/or developed underground space are first identified as the three first-level factors. Considering the important influence of water to Jinan City, which is called City of Spring, the hydrology is suggested as another first-level factor. In addition, according to the comprehensive field investigation, goaf subsidence is determined to be another first-level factor.

The Pilot Zone belongs to the Luxi stratigraphic of the North China zone in the North China-Chaidamu strata. It is generally a monoclinic structure with the Paleozoic northward slope. The terrain belongs to the Yellow River alluvial-diluvial plain. The south of the Yellow River is the mountain plain, which is high in the southwest and low in the northeast. From the top to the bottom, the layer distribution is, in order, the Quaternary, Neogene, Cretaceous, Jurassic, Triassic, Permian, Carboniferous, Ordovician, Cambrian, Taikoo Taishan Group (Zhang et al. 2014).

Hydrological conditions

Measures are taken to prevent the impact from groundwater and surface water during the development and utilization of underground space. The surface water bodies in the Pilot Zone mainly include the Yellow River, Xiaoqing River, Muma River, Xingji River, Dasi River, Lanshi River, Xingjiadu Yellow River Canal, etc. The Baiquan Spring Group is exposed in the southeast corner of the Pilot Zone. According to the hydrodynamics influences, the impact range of the Yellow River and the ditches is set to be the occupied area and the 100m outside the boundary. Other small rivers are not considered for the evaluation.

Hydrogeological conditions

During the foundation excavation process, the Quaternary diving distribution in the shallow area of the Pilot Zone was changed due to hydrodynamic conditions. Infiltration, flowing soil, and quicksand might be caused, which will affect the construction and even lead to the sloping of the foundation pit. In the shallow layer of underground space, the groundwater type is mainly the pore phreatic water in a loose rock mass. There is no favorable aquifer reservoir due to the lithology of the mainly water-bearing rock group being silt, silty clay, etc., and the thin layer of fine sand distribution only in the local region. The water yield property of shallow groundwater is less than 500 m^3/d, the water level of layer pore water is 2-4 m in periods of drought, and is 1.5-3 m in rainy periods. Groundwater enrichment and minimum buried depth of groundwater level are the two subfactors considered in the evaluation.

Engineering geological conditions

Soft soil, collapsible loess, and fault are the three considered factors that impact the development and utilization of underground space. The lithology of the 0-10 m soil in the Pilot Zone is mainly silt and silty clay, and there are 3.5-5 m of clay distributed below 10 m. For soft soil with high water content, due to the high compressibility, low strength, low water permeability, high thixotropy, and other engineering characteristics, consolidation settlement under the action of additional stress would be produced, resulting in ground subsidence that leads to adverse impacts and damage to building safety and construction. The soft soil in the study area, composed of silt and silt soil, is mainly distributed near the banks of the Yellow River, the Xiaoqing River, and the Daming Lake. Collapsible loess distributes in the south of Xiaoqing River, with a buried depth of fewer than 10 m and thickness of less than 5 m. With a small amount of white hyphae-like calcareous tuberculosis, membrane, and vertical joints, it is easy to cause collapsibility when exposed to water and load. Collapsible loess excavation in deep foundation pits will have adverse effects on the construction of the slope. It is not easy to use engineering measures to avoid the unpredictable and extremely catastrophic effects of fault activity. The secondary effects of fault activity include sand liquefaction and induced soil instability. The large-scale faults in the first-class area are Qihe-Guangrao fault, Miaolang-Jiaobin fault, Jinan-Sungen fault, Sangzidian fault, Woniushan fault, Dongwu fault, etc., among which the Qihe-Guangrao fault is deep in the area. Fault structure, rock, and soil mechanics are selected as the sub-factor for engineering geological conditions.

Building foundations and exploited underground space

1) Distribution of building foundations and exploited underground space

Mid-rise buildings with more than three floors and less than ten floors are mainly distributed in Jiyang County, Sangzidian Chemical Park, Daqiao Town, Xinyang Coal Mine Industrial Plaza, Sungeng Town, Cuizhai Town, and the south of the Yellow River, with an area of about 90 km^2. The high-rise buildings in the area are scattered area, mainly including Minghu Hotel (22 floors) on the north side of Minghu Lake in Jinan City, Lakeside Court (26 floors), and three small high-rises in Baihe Garden. Due to the needs of the building foundation and its own functions, most of the mid- and high-rise buildings have 1-2 floors of the basement. The depth of the foundation pit is mostly greater than 10 m, and the depth of the occupied underground space is about 40 m.

2) The influence of mid- and high-rise buildings on the development of underground space

Stress load on the foundation soil will be increased by the continuous growth of mid- and high-rise building groups, which would cause prominent uneven subsidence. The influence depth of the building foundations on the underground space is determined based on the parameters in the "Lishui Underground Space Resource Assessment" (Lu, 2009), as shown in **Table I**. It is not appropriate to develop massive underground space within 10 m, 30 m, and 100 m below the original low-rise building, mid-rise, and high-rise buildings, respectively.

In addition, underground space should not be developed in large quantities under the railway and other municipal facilities. In the evaluation, it is assumed that the average depth of 10 m below the urban railway and other municipal facilities is not included in the underground space resources that can be reasonably developed.

Restrictive factor investigation

According to the results of the comprehensive geological survey, the largest geological environmental problem in the area is the coal mining goaf, which might have a negative impact on the planning and management of the Pilot Zone. The suspended surface rock and soil layers caused by the mined ore body will become bent and deformed under the action of gravity (Peng et al. 2018), which will lead to mining subsidence. For urban construction, some important facilities, such as water pipes, cables, gas pipes, and heating pipes will be affected by the mining subsidence. In addition, the development of underground space at the location of the goaf will increase the instability of the overburden rock and soil layer. Unwish impacts like slope instability can be induced if there is soil layer distributed around the goaf during the construction process and will affect the construction safety.

Two scaled coal mines −the Jiyang and Gaowang coal mines− hold abundant coal resources in the Pilot Zone. Mining the goaf has caused subsidence in the Jiyang coal mine regions. With the further exploitation of coal resources, the area of the goaf and subsidence will be further expanded, as shown in **Figure 2**. The main mining goaf is located to the west of Cuizhai and north of Daqiao Town. As of July 2017, the mine has formed four mining regions named 1-4 mining regions. The survey statistics are shown in **table II**.

Since the Gaowang mine is currently undergoing the exploration application process as well as for the prospecting right, no mining activities have been carried out. According to the field investigation, no mining goaf and subsidence have been found in the area.

TABLE II. SURVEY STATISTICS OF THE MINING GOAF AND SUBSIDENCE AREA IN JIYANG COAL MINE

Mine part No	Goaf area (m^2)	Subsidence area (m^2)
1	615 327.18	1 437 318.96
2	1 898 647.68	3 614 630.52
3	635 993.64	1 992 646.74
4	333 330	1 371 319.62
Total	3 483 298.5	8 415 915.84

Factor weight determination

The export questionnaires survey method was conducted for this evaluation stage. Seven experts with adequate knowledge and professional experiences were invited to participate in the decision-making. Among them, there were five professors with expertise in hydrological and geological engineering, as well as an administrative executor from the local government with a focus on city planning, and officer from the environmental protection department.

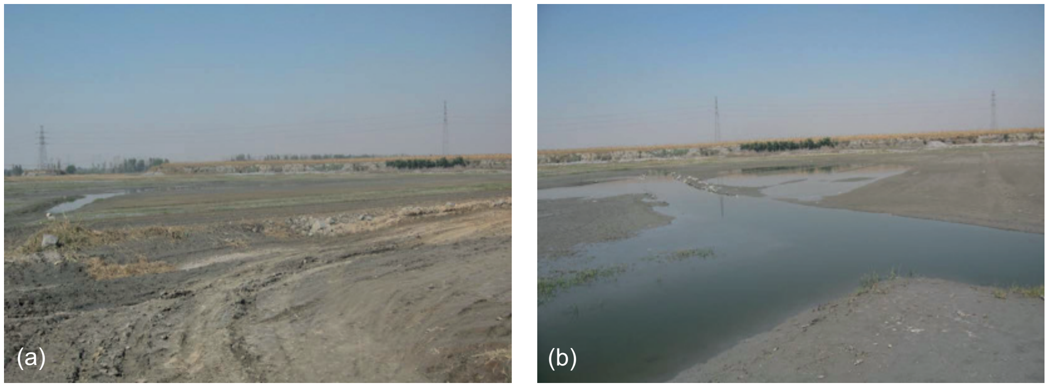

Fig. 2. Survey pictures of mining goaf: (a) the northwest subsidence of Sijiazhuang Village, b) the swamo of the northwest subsidence of Sijiazhuang Village

TABLE I. DEPTH OF INFLUENCE OF GENERAL BUILDING FOUNDATIONS ON THE DEVELOPMENT OF UNDERGROUND SPACE RESOURCES IN SOIL LAYERS (Lu, 2009).

Building category	Building height (m)	Limiting depth (m)
Low-rise building	≤9	10
Low-rise building	9-30	30
Low-rise building	≥30	50-100

According to the contribution and importance of the participating evaluation factors, weights were given by using the expert scoring method, as shown in **table III**.

According to the geological environmental conditions of the work area, the availability of underground space for development is determined as four levels: excellent, good, medium, and poor, as shown in

Here xi, vi represent the value of the factor and evaluation criteria, respectively **table IV**.

Membership function for level I-Excellent:

$$u_{i2} = \begin{cases} 1 & (x_i \geq v_1) \\ (x_i - v_2) / (v_1 - v_2) & v_1 > x_i > v_2 \\ 0 & x_i \geq v_2 \end{cases} \tag{2}$$

Membership function for level II-Good:

$$u_{i2} = \begin{cases} 0 & (x_i \geq v_1 | x_i \geq v_3) \\ (v_1 - x_i) / (v_1 - v_2) & v_1 > x_i > v_2 \\ (x_i - v_3) / (v_2 - v_3) & v_3 \geq x_i \geq v_2 \end{cases} \tag{3}$$

Membership function for level III-Medium:

$$u_{i2} = \begin{cases} 0 & (x_i \geq v_2 | x_i \geq v_4) \\ (v_2 - x_i) / (v_2 - v_3) & v_3 > x_i > v_2 \\ (x_i - v_4) / (v_3 - v_4) & v_3 \geq x_i \geq v_4 \end{cases} \tag{4}$$

Membership function for level IV-Poor:

$$u_{i2} = \begin{cases} 0 & (x_i \geq v_3) \\ (v_3 - x_i) / (v_3 - v_4) & v_4 > x_i > v_3 \\ 1 & x_i \leq v_4 \end{cases} \tag{5}$$

Here x_i,v_i represent the value of the factor and evaluation criteria, respectively.

RESULTS AND DISCUSSION

Suitability evaluation of shallow underground space

Integrated with 17 representative boreholes, the evaluation results of shallow underground space are

TABLE III. EVALUATION FACTOR AND WEIGHT.

Factor	Factor	Hydrology	Hydrogeological		Engineering geology		Mining subsidence area	Building foundations and existing underground space	
	Weight (%)	20	15		15		30	20	
Sub-factor	Sub-factor	U	U1	U2	U1	U2	U	U1	U2
	Weight (%)	100	70	30	60	40	100	50	50

TABLE IV. EVALUATION CRITERIA OF UNDERGROUND SPACE AVAILABILITY.

Level	Factors		Availability rating of underground space development			
			I-Excellent	II-Good	III-Medium	IV-Poor
Hydrology	Surface water(U)[a] (m)		>100	-	-	<100
Hydrogeologic	Groundwater enrichment(U1) (m^3/d)		<500	500-1,000	1,000-3,000	>3,000
	Minimum buried depth of groundwater level(U2)[b] (m)		>10	7-10	3-6	<3
Engineering geology	Fault structure (U1)(m)	gener fault	100	50-100	10-50	<10
		active fault	500	250-500	50-250	<50
	Rock and soil mechanics (U2)		Excellent	Good	Medium	Poor
Mining subsidence area	Mining subsidence (U)		Less prone	-	-	Prone
Building foundation and existing underground space	Ground space facility type(U1)		No special land type.	-	-	Various types of building distribution [c]
	Developed underground space(U2)		None	Small scale	Utility facility [d]	Existing subway

a: Distance from the Yellow River and reservoir.
b: more than the underground space development depth.
c: subways, overpasses, major engineering construction project bases, etc.
d: Existing building basement, civil air defense works, pipelines, etc.

shown in **table V**. Excellent level areas are mainly distributed in the northern areas of the Yellow River, except for Jiyang Coal Mine, Gaowang Coal Mine, Jiyang County, Laoshan Reservoir, New Material Industrial Park, and Daqiao Town. There exists no large surface water in this area. The aquifer in the shallow layer has poor water-richness, and there is no distribution of soft soil and collapsible loess. Except for the mining area, it is a less prone zone for mining subsidence. In addition, there is no special land type at ground level. Underground space is basically untapped, and hence the comprehensive level of suitability evaluation is excellent.

Good level areas are located in the south of the Xiaoqing River and north of the Ring Expressway. There is no large surface water body distribution in this area. The shallow aquifer has poor water-richness. There is no soft soil and collapsible loess distribution. There are large-scale ground-level buildings like the flyover bridge. The development of underground space is small, and therefore the comprehensive level of suitability evaluation is good.

Medium level areas are distributed in parts of the south of the Yellow River and north of the Xiaoqing River. There is no large surface water body distribution in this area. The shallow aquifer has poor water-richness. The surrounding rock stability and engineering geological conditions are poor. Soft soil is distributed, which is a restrictive factor for the development of the underground space area. There is no special land type for ground buildings. The development level for underground space is relatively low, and hence the comprehensive level of suitability evaluation is medium.

Poor level areas are distributed in Jiyang Coal Mine, Gaowang Mining Area, Yellow River, Laoshan Reservoir, Jiyang County, New Material Industrial Park, Daqiao Town, and the south of the Ring Expressway. Jiyang Coal Mine and Gaowang Mining Area are high-prone areas for mining and subsidence, and the Yellow River and Laoshan Reservoir are the main surface water bodies in the area. Jiyang County, New Material Industrial Park, Daqiao Town, and south of the Ring Expressway are concentrated distribution areas for ground-level buildings. The development level for underground space is relatively large, and there is soft soil and collapsible loess distribution. Therefore, the comprehensive level of suitability evaluation is poor.

TABLE V. SUITABILITY EVALUATION RESULTS OF SHALLOW UNDERGROUND SPACE BASED ON THE 17 REPRESENTATIVE BOREHOLES

Location	Membership degree				Comprehensive level
	Excellent	Good	Medium	Poor	
1	0.627	0.373	0	0	Excellent
2	0.605	0.395	0	0	Excellent
3	0	0.108	0.302	0.590	Poor
4	0.440	0.395	0.165	0	Excellent
5	0.464	0.376	0.160	0	Excellent
6	0	0	0.375	0.625	Poor
7	0	0	0.350	0.650	Poor
8	0.558	0.442	0	0	Excellent
9	0.602	0.350	0.048	0	Excellent
10	0.525	0.475	0	0	Excellent
11	0	0	0.331	0.669	Poor
12	0	0.109	0.487	0.404	Medium
13	0	0	0.484	0.516	Medium
14	0.501	0.322	0.177	0	Excellent
15	0	0	0.310	0.690	Poor
16	0.423	0.577	0	0	Good
17	0	0	0.375	0.625	Poor

Comparison of restrictive factor management programs

According to the current situation of mining status in Jiyang Coal Mine, the feasible treatment plans for the goaf include perfusion filling and secondary development of the landscape. Costs and benefits in terms of economic, social, and environmental aspects are compared and analyzed.

Treatment using perfusion filling

The perfusion filling method is one of the most common ways for the treatment of goaf. The advantage of perfusion filling is obvious, which is that it can turn all the coal subsidence areas into suitable construction areas. The cost of treatment mainly includes two parts: construction of the perfusion hole and the high-pressure grouting in the goaf.

The Jiyang Mine Field is a horizontal or near-horizontal coal seam, which is a hard roof with a recovery rate of > 60%. The "upper three zones" of the goaf have good connectivity. According to the "Technical Specifications for the Foundation Treatment of Coal Mine Goaf Construction" (GB) 51180-2016), a perfusion hole is made with an equilateral triangle, in which the hole spacing is 30 m. The depth of the perfusion hole is determined to be 480 m according to the depth of the 7th coal seam, as shown in **table VI**. The drilling price is in accordance with the engineering geological drilling budget standard in the "Shandong Geological Exploration Budget Standard". Drilling price is determined as \$80/m (all costs are in US dollars) based on V-grade siltstone rock. The drilling cost is the drilling length multiplied by drilling price, which is 1858080 m× \$80/m =\$148.6M.

TABLE VI. PERFUSION HOLE DRILLING LENGTH TABLE.

Mining region No.	Coal layer developed	Goaf area (m^2)	Hole spacings (m)	Holes number	Depth (m)	Total drilling depth (m)
1	5, 7	615 048	30	683	480	327 840
2	1, 7	1 898 861	30	2110	480	1 012 800
3	1, 7	636 140	30	707	480	339 360
4	1, 7	333 592	30	371	480	178 080
Sum	-	3 483 641	-	3871	480	1 858 080

The volume of the goaf is calculated according to the equation “mining area volume = producing resource reserve/apparent density”. The accumulated resource reserves of the mine are 4.866 million tons, and the apparent density is the average of the 1st, 5th, and 7th coal seams, as shown in **Table VII**. Goaf volume is calculated by the producing resource reserve (4 866 000 t) divided by the apparent density (1.39 t/m^3), which is 3.5 million m^3. Because of the subsidence of the current surface, the volume should be removed from the filling volume of the goaf. According to the design solutions of restoration of the geological environment of the mine by Shandong Xinyang Energy Co., Ltd, the volume of subsidence is taken as 610 000 m^3. Then the volume of the goaf to be filled is 350-61 = 2.89 million m^3. Considering the factors of hole depth and grouting pressure, it is proposed to use cement mortar as the filling material. Take \$77.8/m^3 as the unit price refers to the grouting treatment project of Hongshan goaf with the mortar type of M5 and consistency of more than 200 mm. Therefore, the filling cost is calculated by the volume of goaf to be filled multiplied by the unit price of grouting material, which is 2.89 million m^3 × \$77.8/m^3 = \$224.8M.

TABLE VII. APPARENT DENSITY CALCULATION OF XINYANG COAL MINE.

Coal seam	1	5	7	Average
Apparent density (t/m^3)	1.35	1.44	1.38	1.39

The construction cost of the goaf filling treatment project is \$148.6M+\$224.8M = \$373.4M.

Many benefits can be acquired in terms of social, environmental, and economic aspects. The implementation of the goaf treatment project can timely protect and restore the natural ecological environment, and effectively eliminate the hidden dangers of geological disasters caused by mining activities. Within the reclamation land, the regional ecological environment can be improved due to the re-planting of vegetation and plants. In addition, the ecological balance can be effectively restored through the treatment of goaf, which can conserve water sources, preserve soil and water, control soil erosion, prevent land degradation, reduce the frequency of flood disasters, and create a good ecological environment for future production and utilization. Furthermore, after the completion of the treatment project, all the original coal mining subsidence areas will become suitable construction areas, which will be increased by more than 6.66 km^2. The economic benefits are significant. Assuming a land remising price of \$700/m^2, the total land sales income will increase by more than \$3.11 billion.

Proper secondary development for landscape

The secondary development of goaf and subsidence areas is beneficial to the ecological environment. Xuzhou, a city in Jiangsu province, is a successful case of the management of mining goaf and subsidence. The Pangzhuang Coal Mine in Jiuli District of Xuzhou holds rich underground mine resources. Most of the subsidence areas have accumulated water, which varies in-depth and is polluted due to the decades of underground mining with a subsidence area of 31.2 km^2. Jiuli Lake Wetland Park was then built based on the natural ecological characteristics of the wetland, which was beneficial to protecting and rehabilitating the wetland ecosystem for maintaining biodiversity, purifying water, regulating the climate, recreation, and other functions. Nowadays, the ecological environment of the Jiuli Lake wetland has been significantly improved. For example, the main water quality has been upgraded from Class IV to Class III. Wild animals and plants and other wetland resources have been effectively protected. The ecological environment provides abundant food sources and suitable habitats for birds and other organisms. The goaf and subsidence management project won the “China Habitat Environment Model Award” in 2015. Another successful implementation of a mining park is in Huaibei, Anhui Province, integrating tourism, leisure, and education with local mining relics. Regarding the treatment of mining goaf and subsidence in Pangzhuang Coal Mine of Xuzhou and Huaibei of Anhui Province, the preliminary costs and benefits are analyzed.

The cost was \$97.4M, involving landscape lake excavation, facilities construction of water diversion, landscape construction, and seepage prevention. As for landscape lake excavation, the main cost was the earthwork excavation and migration. Relying on the existing four mining regions, the maximum depth of excavation (refer to Huashan Lake) was taken as 5 m, and the average depth is 2.5 m considering the demand for leisure cruise ships. The cost of earth and stone works was 389 million yuan, shown in **table VIII**. The cost of water diversion facilities was mainly due to the construction of ditches. The four lakes

TABLE VIII. COST CALCULATION OF SECONDARY LANDSCAPE DEVELOPMENT.

Item	Action amount		Unit price	Cost (million dollars)
Landscape lake excavation	Subsidence area (8.415 million m^2)	Average excavation depth (2.5 m)	$2.87/$m^3$ (*)	60.51
Facilities construction of water diversion	Length of the ditches (5 km)	Width of the ditches is (5 m)	500 000/km	0.39
Landscape construction	Mining landscape ($7.78M)	Lake leisure landscape ($15.56M)	-	23.34
Seepage prevention	subsidence area (8.415 million m^2)	-	$1.56/$m^2$	13.09

are connected through ditches. At the same time, the lakes in the second mining area are connected with the Xingjiadu main channel. The total construction cost was $0.39M. The landscape construction was mainly for the construction of the original industrial square coal mining landscape and the construction of the lake leisure landscape. To maintain a stable water level of the artificial lake, it was necessary to prevent the lake bottom from being treated. According to the dynamic observation data, the Quaternary diving water level is buried 2 to 4 m deep and the seasonal variation is 1 to 2 m. Because the bottom layer of the landscape lake is mainly composed of loess, silty sand, and sandy clay, the overall water permeability is good. HDPE anti-seepage membrane, tailored for artificial lake characteristics was selected as the Anti-seepage treatment material. The HDPE has good mechanical properties, resistance to cracking and leakage caused by foundation settlement, high penetration resistance, simple construction, easy construction quality inspection, and low engineering cost specialty. The cost of the anti-seepage project was $13.1M.

The benefits, especially for the environmental aspect, are remarkable. The construction of landscape lakes can improve the regional living environment for the surrounding people with minimum damage. Through the construction, a new ecological balance would be established, and a water body viewing and leisure place in the Pilot Zone could be formed. In addition, the landscape can derive industrial service chains such as lake fishery farming and surrounding tourism development, which will boost economic development within a few tens of kilometers. Indirectly, the prices of surrounding commercial housing will increase, which will have immeasurable economic benefits.

CONCLUSIONS

A four-stage evaluation framework with fuzzy mathematics comprehensive evaluation method was adapted and proposed in combination with restrictive factors and management programs. With the framework, the sustainable evaluation result could find out the key restrictive factors and the methods to avoid or modify the constraints due to geological conditions. The development of underground space plays an important role in optimizing the spatial layout and improving the overall development quality of Jinan City. A geological survey was carried out in the Pilot Zone which found that mining area subsidence is the key restrictive factor for the development of underground space. Considering the influencing factors of hydrogeology, engineering geology, building foundations, and developed underground space, the suitable level was assessed through the fuzzy comprehensive evaluation method. Potential problems and suggestions when developing different types of underground projects are proposed, which provides a reference for pratical management and planning.

As for restrictive factors of the mining subsidence areas, comparison results of cost and benefit between using perfusion filling treatment and secondary development of landscape indicate that expeditions and tourism projects might be preferable. Jiyang Coal Mine has been mined for more than 10 years, forming a large number of underground wells and roads, with mature lighting, ventilation, and drainage systems. The existing comprehensive underground facilities can be secondarily developed, turning waste into treasure, and becoming the highlight of Jinan's New and Old Growth Driver Conversion Pilot Zone.

Although this study provides an integrated yet comprehensive framework for the suitability evaluation of sustainable underground space development, it still has several limitations: (a) the evaluation criteria rely heavily on experts' cognitions, (b) the calculation of management programs cost was collected from the local market, which may not be representative and consistent, therefore, more effort should be made to adopt the price and make it as accurate as possible, and (c) the uncertainty of multi-factor interaction should be further studied.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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