Resource and Environmental Carrying Capability Assessment of Underground Space in Yuzhong Peninsula in Chongqing

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Abstract: The rational development of urban underground space resources has attracted much attention as an important measure to deal with the urban population, resource, and environmental crises. Resource and environmental carrying capability (RECC) is a key parameter to measure the sustainable development of underground spaces, which is very important for the sustainable development of regional economy and environment. Considering the scarcity, irreversibility, and geological constraints of urban underground spaces, the assessment analysis model and assessment index system were determined according to the actual conditions of Yuzhong Peninsula in Chongqing. The assessment index system comprises the socioeconomic development, resource-carrying capacity, and environmental vulnerability. The resource-carrying capability has a positive effect on the assessment result, while socioeconomic development and environmental vulnerability have a limiting effect. According to urban planning policies and utilization experience, the underground space was divided into three assessment layers, namely, a shallow layer (0–10 m underground), subshallow layer (10–30 m underground), and deep layer (30–100 m underground). The remaining exploitable capacity of the underground space and RECC of the shallow, subshallow, and deep layers in Yuzhong Peninsula were calculated using a self-developed assessment system.

1. Introduction

Resources and environment are the basis of human survival and development. However, excessive human economic activities have seriously damaged the ecological balance, creating great challenges in terms of the resource and environmental carrying capability (RECC) [1-3]. Underground spaces are a scarce and irreversible resource, which cannot be recovered easily once developed [4-5]. Therefore, an RECC assessment [6-7] should be performed to guide underground space planning.

Park et al. [8] introduced the concept of carrying capability into the field of human ecology with the belief that the number of people carried by an area can be determined by the food resources. RECC...
considers not only the resource-carrying capability but also the socioeconomic development and environmental vulnerability (EV). Previous studies mainly focused on the assessment of the suitability and exploitation potential of underground space development [9-13], without fully considering the coordination relationship between urban socioeconomic construction and underground space resources and environment. Because of the differences in the endowment of regional resources and environment and the characteristics of regional development, a unified index system and an analysis model can be built by using only RECC.

In this study, a multilevel assessment index system and an assessment analysis model of underground space RECC were established by considering socioeconomic development, resource-carrying capability, and EV. Then, an automatic RECC assessment system was developed based on GIS technology. Finally, the remaining exploitable capacity (REC) of the underground space and RECC of the shallow, subshallow, and deep layers of the underground space in Yuzhong Peninsula in Chongqing were calculated.

2. Methodology

Urban underground space RECC refers to the intensity and scale limit of various human activities in a certain space–time scale under the condition of rational utilization of underground space resources and the virtuous cycle of ecological environment.

2.1. Assessment area overview

The assessment area is Yuzhong Peninsula in Chongqing, China. It is located at the intersection of the Yangtze River and Jialing River. The expanse of the study area is about 9.8 km², with an elevation range of 150–400 m, as shown in Figure 1. The area extends from Eling in the west to Chaotianmen in the east, and the two rivers form its north and south boundaries. As the core urban area of Chongqing, the Yuzhong Peninsula contains dense surface buildings, including a considerable number of high rises. However, the disorderly excavation and development history has resulted in a lack of rational planning, causing various urban planning problems.

![Figure 1. Schematic diagram of the grid cell division of the study area](image)

2.2. Assessment unit division

According to the experience of underground space utilization planning, the underground space of the assessment area was divided into three layers, namely, a shallow layer, subshallow layer, and deep layer. The shallow layer is the underground space extending from the surface to 10 m underground. It is the most widely used space domain for human beings and also the main space domain for civil buildings and underground service facilities. The subshallow layer refers to the underground space from 10 m to 30 m underground; underground transit and large-scale fundamental infrastructure mainly exist in this area. The deep layer refers to the underground space from 30 m to 100 m...
underground. Some civil air defense projects and pile foundations of super high-rise buildings can be found in this layer. Each layer was divided into a grid of $5400 \times 3600$ cells with sides 1 m long. Based on the layering assessment mode, the RECC assessment of each layer was completed by considering assessment indexes comprehensively.

2.3. Assessment index system

The assessment index system of the urban underground space RECC was established by considering the social economy and underground space resources and environment. It is a multilevel system containing a target layer, criterion layer, and the index layer, as shown in Table 1. Science and ease of operation are the principles for establishing the index system. The assessment target was to obtain the urban underground space RECC of the study area. The rule layer has three parts, i.e., socioeconomic development, resource-carrying capacity, and EV. Socioeconomic development reflects the degree of economic development and social progress in the study area. Resource-carrying capacity reflects the material and space foundation of underground space construction and development. EV reflects the impact of human activities on the environment. The index layer is the most basic level of the index system guidelines layer indicators of the specific characteristics of indicators, constituted by measurable indicators. The weights and basis of assessment of the indexes were determined by qualitative and quantitative analyses by the method of AHP [14-15] after expert consulting.

Table 1. Urban underground space Resource and environmental carrying capability (RECC) assessment index system

| Target layer | Rule layer | Index layer |
|--------------|------------|-------------|
| Urban underground space resource and environmental carrying capability | Socioeconomic development | Population aggregation |
| | Resource-carrying capacity | Economic development level |
| | | Resource capacity |
| | | Engineering geology |
| | | Geologic hazard |
| | | Regional geology |
| | | Surface environment |
| | | Groundwater condition |
| Environmental vulnerability | | Basic index |
| | Population density | Population flow intensity |
| | Regional per capita GDP | Land grade |
| | | Remaining exploitable capacity |
| | | Saturated compression strength |
| | | Rock mass integrity |
| | | Hazard type |
| | | Earthquake magnitude |
| | | Geological structure |
| | | Land slope |
| | | Land subsidence |
| | | Water layer thickness proportion |
| | | Water abundance |

2.4. Assessment analysis model

Considering the scarcity, irreversibility, and geological constraints of urban underground space resources, the assessment analysis model of the urban underground space RECC was established by incorporating the actual situation of the study area.

2.4.1. Socioeconomic development. Socioeconomic development (SED) is an important measure of the level of social development and modernization of a region as a whole. SED is closely related to the population aggregation degree (PAD) and economic development level (EDL) and can be expressed as follows:
where $S_{ed}$, $P_{ad}$, and $E_{dl}$ are the values of SED, PAD, and EDL, respectively. PAD is positively correlated with the population density and population flow intensity. EDL reflects the scale and level of social and economic activities in the study area and is determined by the regional per capita GDP and land grade.

2.4.2. Resource-carrying capacity. Owing to the scarcity of underground space resources and constraints of geological conditions, the resource-carrying capacity (RCC) will be higher with more REC and better engineering geology condition (EGC). The relationship can be expressed as shown in equation (2):

$$R_{cc} = \sqrt{\frac{1}{2} (R_{cc}^2 + E_{gc}^2)}$$

(2).

where $R_{cc}$, $R_{ec}$, and $E_{gc}$ are the values of RCC, REC, and EGC, respectively. REC refers to the proportion of exploitable resource space in the total underground space. The depth of influence of the existing buildings can be obtained according to the data in Table 2. This depth is used to calculate the developed resource capacity. EGC is determined by the saturated compressive strength of rock and integrity of rock mass.

Table 2. Influence depth of the existing environment and buildings

| Assessment index | Square | Green land | Road | Relic | Civil air defence | Aboveground buildings | Underground structure |
|------------------|--------|------------|------|-------|------------------|-----------------------|----------------------|
| Influence depth  | 3 m    | 3 m        | 5 m  | 5 m   | Full depth       | Pile foundation       | Depth from the top to the bottom of the structure |

2.4.3. Environmental vulnerability. EV is measured by four comprehensive indexes: geologic hazard (GH), regional geology (RG), surface environment (SE), and groundwater condition (GC). GH represents the geological disaster with the greatest risk according to the most disadvantageous principle. RG is determined by earthquake magnitude and the geological structure. SE is determined by the land slope and land subsidence, and GC is determined by the proportion of thickness of the water layer and water abundance. EV is calculated from equation (3) as follows:

$$E_v = \sqrt{\frac{1}{4} (G_{bh}^2 + R_b^2 + S_e^2 + G_c^2)}$$

(3).

where $E_v$, $G_{bh}$, $R_b$, $S_e$, and $G_c$ are the values of EV, GH, RG, SE, and GC, respectively.

Table 3. Scoring basis of the assessment indexes

| Basic index                        | Classification and scoring |
|------------------------------------|----------------------------|
| Population density (people/km$^2$) | 4 | 3 | 2 | 1 |
| ≥ 1000                             | 500-1000 | 500-50 | < 50 |
| Population flow intensity           | ≥ 1 | 0.5-1 | 0.2-0.5 | < 0.2 |
| Regional per capita GDP (10000 yuan) | ≥ 15 | 10-15 | 5-10 | < 5 |
| Land grade                         | I | II | III | IV |
| Remaining exploitable capacity (%) | ≥ 80 | 50-80 | 20-50 | < 20 |
| Saturated compression strength (MPa) | ≥ 23 | 15-23 | 7-15 | < 7 |
After calculating the scores of the three rule layer indexes, the RECC can be calculated from equation (4) because of the positive effect of RCC and the limited effect of SED and EV.

\[ R_{\text{ecc}} = \frac{R_{\text{cc}}}{S_{\text{ed}} \times E_{\text{v}}} \]  

(4).

where \( R_{\text{ecc}} \) is the values of RECC, and the other notations are as defined earlier. The score of a comprehensive index is the average of the related basic indexes, which can be obtained according to the data in Table 3.

![Fig 2. Automatic Resource and environmental carrying capability (RECC) assessment system](image_url)

**Figure 2.** Automatic Resource and environmental carrying capability (RECC) assessment system

### 2.5. Automatic assessment system

The main program of the proposed system was developed based on ArcGIS Engine v 10.2 and Microsoft Visual C# 2017 platform, and the database was constructed using Microsoft SQL Server 2019. This system integrates common functions such as map loading and layer browsing in GIS, as shown in Figure 2. In addition, the system contains two functional modules, namely, a data
management module and an assessment analysis module. The data management module provides the management of basic assessment data, models, and results. The assessment analysis module supports setting vertical division sections freely, and conducts the REC and RECC assessments.

3. Results analysis
The REC and RECC assessments of each underground space layer were conducted. The results are shown in Figure 3.

![Figure 3. Remaining Exploitable capacity (REC) calculation and Resource and environmental carrying capability (RECC) assessment of each underground space layer](image)

Most underground structures, including building pile foundation, underground parking lots, and underground storage facilities, are densely distributed in the shallow layer. The average proportion of the REC in the shallow layer is approximately 80.5%. Deep, large underground structures are mainly distributed around Lai-Fu-Shi square, Chao-Tian-Men wharf, and Jiefangbei business district, and the
pile foundations are long, extending to the subshallow layer. The average proportion of REC in the subshallow layer is approximately 92.6%. The pile foundation of a few buildings can reach depths greater than 30 m, that is, the deep layer. In addition, underground transit facilities may exist in the deep layer, and the average proportion of REC in the deep layer is approximately 96.1%.

The RECC assessment considers not only the REC, but also other assessment indexes. The underground space resource quality is graded from good to bad using grades I–IV. The shallow layer lies in a Quaternary loess accumulation layer and is affected by strong weathering. Hence, the geological conditions near the ground surface are poor. Furthermore, underground buildings and structures are densely distributed in this layer, and the RECC assessment is also easily affected by other assessment indexes on the surface. Therefore, the proportion of RECC assessment Grades III and IV exceeds 71%. The subshallow layer is mainly affected by the rail transit, pile foundations of high-rise buildings, and other factors, and the proportion of UUSR assessment Grades III and IV almost exceeds 19%. The deep layer mainly has RECC assessment Grades I and II, while low assessment grades are distributed in Jie-Fang-Bei, Chao-Tian-Men, and other highly developed areas with super high-rise buildings or poor geological conditions.

4. Three-dimensional visualization system based on iS3

Infrastructure smart service system (iS3) is the first open-source platform for underground infrastructure life-cycle information integration and sharing and provides powerful data management, data analysis, and visualization functions. Each part is encapsulated as a microservice invoked through an API interface. In this study, the data management microservice is invoked to process and standardize multisource heterogeneous assessment data. The term “structure data” refers to the data that can be logically expressed with a two-dimensional table structure, while other types of data include all formats of office documents, text, images, audios, and videos. The relevant data conversion technology based on GIS can be adopted to preprocess all types of data into unified structured data, and the corresponding data structure required for storage should be designed. Then, the analysis microservice is invoked to conduct the REC and RECC assessments using the self-developed assessment system. Finally, the analysis results are sent to iS3 for postprocessing. The visualization microservice is invoked to obtain a three-dimensional RECC grade partition of the study area.

![Diagram of the three-dimensional visualization system based on iS3](image_url)
5. Conclusions
The following conclusions can be drawn from the results of this study.

(1) The assessment analysis model and assessment index system were determined according to the actual situation. The assessment index system comprises SED, resource-carrying capability, and EV. The resource-carrying capability has a positive effect on the assessment result, whereas SED and EV have a limiting effect.

(2) REC and RECC assessments were conducted for each underground space layer, and the REC and RECC both improve with greater depths.

(3) The assessment system can be encapsulated into analysis microservice and integrated into iS3, which realizes the integrated service of assessment data management, assessment analysis, and 3D visualization.

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