Evaluation of urban underground space resources in a delta coastal city

Jianxiu Wang, Yuxin Su
Tongji University, 1239 Siping Road, Shanghai, China 200092
Hanmei Wang, Yujin Shi, Daping Chen
Shanghai Institute of Geological Survey, 930 Lingshi Road, Shanghai, China 200082
Qiwei Gu, Xiaotian Liu
Tongji University, 1239 Siping Road, Shanghai, China 200092

wanghaijuan@tongji.edu.cn ORCID https://orcid.org/0000-0001-5438-8184

Abstract. In the multi-aquifer and multi-aquitard system of a delta coastal city, urban underground space is filled with soil, sediment, and rock mass, as well as groundwater. Underground space can be created by excavating the layered strata. Urban underground space includes man-made structures, such as piles, underground structures, subway tunnels, etc. It is important to know how to evaluate the number of underground space resources. With Shanghai as background and the Zhongshan park urban plan unit as an example, a three-dimensional geological model for all sediment layers was established based on the geotechnical investigation. The number of existing underground structures was estimated using collected data. An underground space estimation method is introduced. The proportion of different layers was calculated using a geological model that corresponded to the shallow-middle-deep urban underground space conceptual plan, which can be referred to by underground space planning.

1. Introduction
Some coastal cities are located on multi-aquifer and multi-aquitard (MAMA) layers. Geological conditions are essential in the evaluation of underground space resources to avoid potential urban geological disasters. Currently, the demand for underground space is increasing due to urbanization. A reasonable evaluation of underground space resources in MAMA is necessary for sustainable development in cities. In Shanghai, shallow underground space has been fully developed and nearly exhausted in some areas of the central city, and the development of deep underground space has been proposed. The amount of shallow underground space and deep underground space must be scientifically evaluated for future further city development.

Sterling et al. used a comprehensive superposition method to investigate the distribution area of underground space resources that can be developed and utilized in Minneapolis under special geological conditions [1]. Boivin superimposed geology and other factors to obtain a development difficulty rating for Quebec, Canada based on transparency [2]. De Rienzo et al. introduced a GIS-based 3D geological and underground structural model for determining the optimal excavation method in a certain Turin location, which provided great help for the planning and management of underground space development [3]. The suitability evaluation of underground space development as a planning tool and the decision-making support system for using underground space for the sustainable development of coastal cities in Shanghai were proposed.
was first proposed and implemented in Beijing and some coastal cities in China. Tong et al. presented the investigation and evaluation system and model of Xiamen urban underground space resources based on grading the difficulty of engineering suitability of underground space resources [4]. In the underground space resource evaluation, He et al. used the fuzzy mathematics method and the analytic hierarchy process to comprehensively evaluate the regional resource development and utilization of underground space in Beijing geological suitability based on research results, basic conditions, and constraints of combining the underground space resource development and utilization of geological suitability evaluation index system [5]. Xia et al. used the fuzzy comprehensive evaluation method to evaluate the suitability of the city underground development according to the engineering geological characteristics of the Qingdao urban area and the construction experience as well as the analysis of the rock and soil mass, groundwater, geological structure, and soft soil characteristics, including the main constraint of underground space development and utilization of the distribution characteristics of geological factors [6]. Long et al. analyzed the results of a geological survey, such as Guangzhou underground engineering, development, and utilization of the main factors to select factors influencing the evaluation of underground space development and utilization, and used an expert-analytic hierarchy weighting method to determine the weight of factor, set up in Guangzhou city underground space development and utilization of suitability evaluation model of partition, as well as the ArcGIS software to obtain the final suitability evaluation map [7]. Peng et al. summarized the current underground space utilization status in Changsha, as well as the main geological factors affecting the development of underground space in Changsha, which include fault, karst, weathered trough valley, and groundwater, and adopted the multi-factor analysis method to make a subdivision of underground space suitability and put forward engineering measures and suggestions [8]. The existing evaluation of underground space in Shanghai is mainly based on the calculation of unused underground space on a city-wide scale. The information on geological conditions for a concrete planning unit is not enough and should be presented in detail.

In this paper, a typical Shanghai planning unit was selected as a demonstration area, and detailed information on engineering geology conditions, existing underground space, and architectural structures were collected. Three kinds of underground space were defined, and the proportion and distribution of layers were estimated, which was the main innovation of the manuscript. Effective underground space resource was evaluated, and the results can be used in Shanghai urban planning and referred to by other similar cities.

1.1 Background

Currently, the average depth of engineering construction in Shanghai is less than 75 m. The strata are mainly late Pleistocene loose deposits. The lithology includes mainly clayey soil, sand, and silt, where soft clayey soil is widely distributed. Based on sedimentary age, physical characteristics, and mechanical characteristics, the strata are categorized into nine engineering geological layers: (1) layer ① (filling), (2) layer ② (brown yellow sallowness clay), (3) layer ③ (silt: shallow sand layer), (4) layer ④ (gray muddy clayey soil), (5) layer ⑤ (gray clayey soil), (6) layer ⑥ (sand or silt), (7) layer ⑦ (dark green-brown yellow clayey soil), (8) layer ⑧ (straw yellow-gray sand and silt), and (9) layer ⑨ (gray clay with silt). Phreatic, micro-confined, and the first, second, third, fourth, and fifth confined aquifers exist in Quaternary loose sediments. Groundwater that flows through the phreatic aquifer, micro-confined aquifer, and the first confined aquifer is often called shallow groundwater, while the groundwater that flows through the second, third, fourth, and fifth confined aquifer is often called deep groundwater.

The Zhongshan park business circle is bordered by Wuyi Road in the south, on the west by Kaixuan Road, and Inner Ring Road of Zhongshan Road, on the north by Wanhangdu Road, and on the east by Huayang Road and Anxi Road in the east, making it a Shanghai sub-center. In the area, there are subway Line 2, 3, and 4 transfer stations, as well as the Zhongshan park, which covers the largest area in the Inner Ring area.
The Zhongshan park mainly consists of a transportation hub and commercial buildings, with an intentionally blurred boundary between the hub and other businesses. Avoiding mutual interference between traffic flow and commercial flow is one of the most difficult challenges in the development of hub commerce. The design of traffic space emphasizes spatial fluency and avoids congestion. However, since commercial space design aims to improve residence time, and coordination of the mutual interference is difficult, it is necessary to develop underground space to resolve the aforementioned contradiction (Fig. 1).

Fig. 1 Schematic of commercial facilities connection around the Zhongshan park hub

1.2 Partition considering layer composition
In quantity evaluation of underground space resources, the guiding ideology of “advancing layer by layer and integrating from zero” was used to establish a complete set of quantity evaluation systems. Shanghai is divided into multiple geological structure partitions based on their layer combination due to varying development degrees of underground space in different areas with different architectural structures that cannot be integrated into a system. The number of underground space resources in different regions can be obtained according to the adaptability of different partition geological conditions to underground space development.

1.3 Underground space resources calculation method
Underground space resources can be divided into four categories based on their exploitation and utilization stage: (1) developed and utilized resources, (2) undeveloped and utilized resources, (3) partially exploitable and utilized resources, and (4) fully exploitable and utilized resources.

The developed and utilized underground space resources were the parts of underground space that have been developed and utilized as basements, tunnels, pile foundations, and a certainly affected range layers. Unexploitable underground space resources existed due to many factors, including mineral and groundwater protection areas. The partially exploitable underground space resources cannot be fully exploited although they may have potential space in some areas. The fully developed and utilized underground space can be fully developed and utilized without the influence of existing structures. See Fig. 2.
1.3.1 Underground space evaluation without considering existing artificial structures
Based on the original borehole data, the underlying contour map was obtained using CAD software. The elevation of each layer was obtained using the collected borehole data. The contour scattered and interpolation calculation contour map was transferred to a scatterplot using coordinates and elevation data of each layer. The amount of underground space can be obtained by differentiating between each formation and location.

1.3.2 Underground space evaluation considering existing artificial structures
The area and depth of various underground structures were used to compute the volume of the occupied underground space resources. The available space was obtained by removing the occupied space resources previously mentioned. However, the underground structures affected a larger volume than the self-occupied space. Underground structures, which bear soil and groundwater pressures, were closely connected with foundation soil layers. The mutual force of the underground structure affected surrounding soil and groundwater. The influenced range of the underground structure was divided into horizontal buffer range and vertical buffer range. The influenced range can be calculated in various ways. The influence range of the foundation can be obtained from the stress diffusion angle (Fig. 3). The number of underground space resources that can be used was obtained by deleting the influenced range and self-occupied space in horizontal and vertical directions.
1.3.3 Underground space evaluation considering existing artificial structures and unfavorable geological conditions

In the area with good quality foundation layers, the remaining space can be taken as the total amount of underground space after deducting the area with built artificial structures and buffer zone. However, for the area with poor quality foundation layers, further analysis and calculations were required.

2. Results

Based on the investigation of the Zhongshan park urban plan unit, the GIS software was used to obtain the equi-thickness map of each soil layer, and the distribution map of the underground buildings in the Zhongshan park was compiled based on the geotechnical engineering investigation report. The space of the underground buildings and the buffer area was estimated, and the number of resources available for the underground space was calculated.

2.1 Formation thickness

For the urban plan unit of the Zhongshan park, the obtained equal thickness of different layers is shown in Fig 4.

**Fig.3** Schematic of influence range under and around buildings (Revised form Beijing Institute of Geological Survey)
11th Conference of Asian Rock Mechanics Society

2.2 Underground structures
The distribution of underground artificial structures in the Zhongshan park is shown in Fig. 5(a). The distribution of the underground pile foundation is shown in Fig. 5(b).

Fig. 5 Distribution map of underground structures of the Zhongshan park
2.3 Underground space resource analysis

The estimation underground space model was established, considering existing artificial structures. The characteristics of the underground space of the Zhongshan park unit are shown in Tables 1–9.

Table 1. Different soil layer divisions.

| Soil serial No. | ② | ③ | ④ | ⑤₁ | ⑤₂ | ⑤₃ | ⑥ | ⑦₁ | ⑦₂ |
|-----------------|----|----|----|-----|-----|-----|----|-----|-----|
| Lithology       | Silty clay | Silty clay | Clay | Silty sand | Clay | Clay | Silt | Silt |

| Soil serial No. | ⑧₁ | ⑧₂ | ⑨₁ | ⑨₂ | ⑩ | ⑪ | ⑫ | ⑬ |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Lithology       | Clay | Clay | Silt | Fine sand | Clay | Silt | Clayey silt | Silt |

Table 2. Volume and percentage of each layer.

| Soil serial No. | ③ | ④ | ⑤₁ | ⑤₂ | ⑤₃ | ⑥ | ⑦₁ | ⑦₂ | ⑧₁ |
|-----------------|----|----|-----|-----|-----|----|-----|-----|-----|
| Volume (×10⁶ km³) | 15.30 | 50.46 | 63.33 | 0.11 | 6.45 | 14.26 | 23.79 | 31.94 | 33.15 |
| Percentage (%)   | 2.33 | 7.69 | 9.65 | 0.02 | 0.98 | 2.17 | 3.62 | 4.87 | 5.05 |

| Soil serial No. | ⑧₁ | ⑧₂ | ⑨₁ | ⑨₂ | ⑩ | ⑪ | ⑫ | ⑬ | Total volume |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|--------------|
| Volume (×10⁶ km³) | 48.70 | 37.58 | 71.02 | 26.42 | 53.31 | 20.95 | 159.71 | 656.47 |
| Percentage (%)   | 7.42 | 5.72 | 10.82 | 4.02 | 3.62 | 3.19 | 24.33 | 100 |

Table 3. Volume and percentage of different layers.

| Lithology | Clay | Silty clay | Clay | Silty sand | Silt | Total volume |
|-----------|------|------------|------|------------|------|--------------|
| Volume (×10⁶ km³) | 15.30 | 50.46 | 192.31 | 377.46 | 20.95 | 656.47 |
| Percentage (%)   | 2.33 | 7.69 | 29.29 | 57.50 | 3.19 | 100 |

Table 4. Volume and percentage of different layers in shallow underground space(0–15 m).

| Soil serial No. | ② | ③ | ④ | ⑤₁ | ⑤₂ | ⑤₃ | Total volume |
|-----------------|----|----|----|-----|-----|-----|--------------|
| Volume (×10⁶ km³) | 15.30 | 15.30 | 29.31 | 0.08 | 0.01 | 60.00 |
| Percentage (%)   | 25.50 | 25.50 | 48.85 | 0.14 | 0.01 | 100 |

Table 5. Volume and percentage of different layers in shallow underground space(0–15 m).

| Lithology | Clay | Silty clay | Clay | Total volume |
|-----------|------|------------|------|--------------|
| Volume (×10⁶ km³) | 15.30 | 44.61 | 0.09 | 60.00 |
| Percentage (%)   | 25.50 | 74.35 | 0.15 | 100 |

Table 6. Volume and percentage of different layers in middle underground space(15–40 m).

| Soil serial No. | ③ | ④ | ⑤₁ | ⑤₂ | ⑤₃ | ⑥ | ⑦₁ | ⑦₂ | Total volume |
|-----------------|----|----|-----|-----|-----|----|-----|-----|--------------|
| Volume (×10⁶ km³) | 0.02 | 5.84 | 63.24 | 0.10 | 2.98 | 14.10 | 19.07 | 1.91 | 107.26 |
| Percentage (%)   | 0.02 | 5.44 | 58.96 | 0.09 | 2.78 | 13.15 | 17.78 | 1.78 | 100 |
### Table 7. Volume and percentage of different layers in middle underground space (15–40 m).

| Lithology      | Silty clay | Clay   | Silty sand | Total volume |
|----------------|------------|--------|------------|--------------|
| Volume ($\times 10^6$ km$^3$) | 5.86 | 80.32 | 21.08 | 107.26 |
| Percentage (%) | 5.46 | 74.89 | 19.65 | 100 |

### Table 8. Volume and percentage of different layers in deep underground space (40–150 m).

| Soil serial No. | $\mathcal{S}_2$ | $\mathcal{S}_3$ | $\mathcal{S}_5$ | $\mathcal{T}_1$ | $\mathcal{T}_2$ | $\mathcal{S}_1$ | $\mathcal{S}_2$ | Total volume |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|--------------|
| Volume ($\times 10^6$ km$^3$) | 0.01 | 3.46 | 0.15 | 4.72 | 30.03 | 33.15 | 48.70 |
| Percentage (%) | 0 | 0.71 | 0.03 | 0.96 | 6.14 | 6.78 | 9.95 |

| Soil serial No. | $\mathcal{S}_1$ | $\mathcal{S}_2$ | $\mathcal{S}_3$ | $\mathcal{S}_4$ | $\mathcal{S}_5$ | $\mathcal{S}_6$ | $\mathcal{S}_1$ | Total volume |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|--------------|
| Volume ($\times 10^6$ km$^3$) | 37.58 | 71.02 | 26.42 | 53.31 | 20.95 | 159.71 | 489.21 |
| Percentage (%) | 7.68 | 14.52 | 5.40 | 10.90 | 4.28 | 32.65 | 100 |

### Table 9. Volume and percentage of different layers in deep underground space (40–150 m).

| Lithology       | Clay   | Silty sand | Clayey silt | Total volume |
|-----------------|--------|------------|-------------|--------------|
| Volume ($\times 10^6$ km$^3$) | 111.88 | 356.37 | 20.95 | 472.38 |
| Percentage (%) | 22.87 | 72.85 | 4.28 | 100 |

### 3. Discussion

Underground space was regarded as the geological space restricted by the geological environment. The current geological environment was important in estimating underground space resources. Further works should be performed in the following aspects:

1. The Shanghai underground space conceptual plan has been re-defined, and further layer division should be carried out according to the new plan.
2. The evaluation of underground space resources should be carried out in different layers and zones.
3. The reasonable buffer method of new and existing underground structures should be discussed in detail and verified in practice.
4. The distributed parameter model should be adopted in the detailed plan model.
5. A big data system of underground information with urban renewal should be established to dynamically update data with city renewal.
6. The initiative to serve urban development and urban disaster prevention should be considered and practiced.

In underground space resource evaluation, the concept of underground space capacity should be defined. Underground space capacity referred to the rate of underground space that can be used in the future to the total underground space within a time-spatial range under a certain technical level. The buffer of the built underground structure and all kinds of potential newly constructed underground structure types, including foundation pit, pile foundation, tunnel, underground pipeline, etc. should be defined in detail. The concept of underground space capacity was used to determine the number of underground space resources was determined with the subsequent underground structure construction. The calculation method of underground space capacity was similar to that of the number of underground space resources that can be effectively used. The volume and buffer zone of artificial structures can be calculated. Through the concept, the number of underground buildings that can be accommodated by the underground space can be obtained.

### 4. Conclusions
(1) The buffer range of the underground structure can be divided into horizontal and vertical buffer zones. According to the stress diffusion angle theory, the number of underground space resources that can be used was obtained by deducting the horizontal and vertical buffer volumes, as well as self-occupied underground space.

(2) According to geotechnical engineering investigation information, the thickness and underground structure distribution of the Zhongshan park unit were obtained.

(3) The lithology, volume, depth, and thickness of different layers in the Zhongshan park unit, which make up the city plan, engineering design, and construction, were estimated and presented.

Acknowledgments
This study is sponsored by the Shanghai Municipal Science and Technology Project (18DZ1201301; 19DZ1200900), Key Laboratory of Land Subsidence Monitoring and Prevention, Ministry of Natural Resources of the People’s Republic of China (No. KLLSMP202101), Suzhou Rail Transit Line 1 Co. Ltd, Xiamen Road and Bridge Group (XM2017-TZ0151; XM2017-TZ0117), China Railway 15 Bureau Group Co., and IGCP Project (663-La Subsidence in Coastal cities).

References
[1] Sterling R L, Barker M, Froise S. Legal and administrative issues in underground space use a preliminary survey of member nations of the international tunneling association 1990 Tunnel and Underground Works Today and Future, Proceedings of the international Congress ed Kriekemans B (Chengdu) pp 379–385
[2] Boivin D J 1990 Underground space use and planning in the Québec City area Tunn. Undergr. Sp. Tech. 5: 69–83
[3] Rienzo F D, Oreste P, Pelizza S 2009 3D GIS supporting underground urbanization in the city of Turin (Italy) Geotec. Geol. Eng. 27: 539–47
[4] Tong L X. 2009 Urban underground space resources evaluation and development and utilization planning (China Building Industry Press)
[5] He J, Zhou Y X, Zheng G S, Wang J M and Liu Y 2020 Geologic suitability evaluation of underground space resources utilization in Beijing Chin. J. Undergr. Space .Eng. 16 :955-966.
[6] Xia W Q, Dong J, He Peng and Xie Y J 2019 Evaluation of the influence of geological factors and suitability zoning of underground space development and utilization in Qingdao Acta Geol. Sin. 93:233-240.
[7] Long R, Zhang F W, Luan S and Li W X 2020 Study on suitability evaluation of development and utilization of underground space in Guangzhou city Northwest Geol. 53:194-206.
[8] Peng B X, Wang X H, Wang H Y and Shu Q 2021 Current situation, suitability evaluation and engineering measures of the development and utilization of underground space in Changsha Urban Surv. 4:190-194+199.