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INFLUENCING FACTORS AND EVALUATION INDEX SYSTEM FRAME FOR THE BEARING CAPACITY OF DEEP UNDERGROUND SPACE IN COASTAL SOFT SOIL CITIES: A CASE STUDY OF SHANGHAI

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Abstract: Shanghai, a coastal megacity built on soft deltaic soil, faces growing demand for deep underground space (DUS) development as its shallow and intermediate layers approach saturation. However, the complex interplay of geological, hydrogeological, and environmental factors significantly constrains the carrying capacity of DUS. This study investigates the bearing capacity of DUS in Shanghai as a representative coastal soft soil city. Through systematic analysis of deep stratigraphic conditions, confined aquifer systems, and environmental geological risks (e.g., land subsidence, liquefaction, and gas escape), the key influencing factors are identified. Special attention is given to the coupled effects of thermal–hydraulic–mechanical–chemical (THMC) processes. Based on these insights, a multi-dimensional evaluation index system is proposed, incorporating geotechnical, hydrogeological, environmental, and spatial utilization factors. The framework provides a basis for carrying capacity assessment under current engineering conditions. The findings offer methodological guidance and geological support for the planning and sustainable development of DUS in Shanghai and similar coastal cities.

Keywords: Deep Underground Space, Coastal Soft Soil, Bearing Capacity, Evaluation index, Influencing Factors Analysis

1. INTRODUCTION

The development of urban underground space (UUS) is an important approach to achieving sustainable urban development. It can effectively alleviate the tension between people and land in modern cities, expand urban space, and improve the urban environment. (Sterling et al., 2012; Bobylev, 2016; Admiraal & Cornaro, 2020; Qiao et al., 2022). However, with the acceleration of urbanization, megacities such as Shanghai, Beijing, Guangzhou, and Tokyo (Kishii, 2016) are facing a series of challenges including continuous population growth, traffic congestion, and resource shortages. The contradiction between the rapidly expanding demand for urban space and the limited availability of spatial resources has become increasingly prominent. Meanwhile, as the development of shallow and middle UUS becomes increasingly saturated, the exploitation of deep underground space (DUS) has become an inevitable trend in addressing the above challenges. (Li et al., 2018; Li et al., 2025).

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As a typical coastal megacity built on soft soil, Shanghai has seen the shallow and middle underground space in its central urban areas approach saturation amid the ongoing intensification of urban development. (Qian and He, 2024)，The development of DUS has become a strategic choice for enhancing urban carrying capacity and achieving sustainable development. However, the development of deep underground space is not merely an extension of shallow or intermediate layers; it faces more complex challenges related to geological conditions, groundwater, and structural stability, making it significantly more difficult. Although Shanghai has accumulated extensive experience in shallow underground development, deep development still requires further investigation. According to the Shanghai Master Plan (2017–2035) (Liu and Zhu, 2020), areas below 50 meters are designated as deep underground space and are a key focus for future urban expansion (Li et al., 2018). However, UUS carrying capacity is constrained by engineering geological and hydrogeological conditions, the coupled effects of thermal–hydraulic–mechanical–chemical (THMC) processes, and the current level of engineering technology(Li et al., 2016; Price et al., 2018). Therefore, it is essential to systematically identify and evaluate the key factors influencing its carrying capacity.

Existing studies have explored the driving forces, limiting factors, and evaluation methods of urban underground space (UUS) development from multiple perspectives. Bobylev (2009), He et al. (2012), and Chen et al. (2018) identified urban population density and per capita GDP as key drivers of underground space development. Li et al. (2013a) emphasized that land prices and construction costs are primary indicators for assessing the economic viability of UUS. Li et al. (2013b) further proposed the "Deep City Method," which integrates four types of underground resources with three urban indicators to establish a scoring system for identifying cities with development potential. Lu et al. (2016) developed a multi-level engineering geological suitability evaluation framework for UUS using the FAHP-TOPSIS method. Regarding constraints, complex geological conditions are recognized as major factors affecting development difficulty and cost (Mukhtar et al., 2019; Lai et al., 2023), while groundwater can compromise structural stability and increase corrosion risks (Mukhtar et al., 2019; Attard et al., 2017). Other factors, such as topography, economic conditions, and land use, have also been considered in suitability assessments (Zhang et al., 2021). He et al. (2020) established a geological suitability evaluation index system based on fundamental and constraint conditions, applying fuzzy mathematics and AHP to assess UUS development in a region of Beijing. Peng and Peng (2018a, 2018b) combined AHP, MUGM, and EM methods within a GIS platform to evaluate construction suitability, potential value, and volumetric capacity. From a safety perspective, Zhou et al.(2024) integrated geotechnical analysis, urban planning theory, and artificial intelligence to develop an intelligent resilience evaluation model, assessing the impact of UUS development on surrounding buildings and enhancing the scientific basis for safe spatial planning.

Existing studies have made some progress in evaluating underground space development, particularly in assessing geological suitability and development potential. However, research on deep underground space has mostly focused on planning, with limited work on the definition and quantitative analysis of carrying capacity. This paper defines underground space carrying capacity as the maximum development intensity that can be supported while ensuring safety and functionality, considering geological conditions, technical feasibility, and societal needs. Taking Shanghai as a case study, this paper reviews its deep underground space development, analyzes key influencing factors and evaluation methods, and proposes an assessment framework suitable for soft soil areas to support future safe and scientific development.

2. DUS IN SHANGHAI

2.1. Current Status of Deep Underground Space Development and Utilization in Shanghai

In recent years, with the continuous intensification of urban construction, the development and utilization of underground space in Shanghai has expanded rapidly. By the end of 2022, approximately 43.000 underground engineering projects had been completed, with a total floor area of about 1.45×10^9 m², encompassing a wide range of functions including transportation, municipal infrastructure, public services, and warehousing logistics. Among these, facilities for daily life services account for as much as 86% of the total, while rail transit and public infrastructure make up approximately 8% and 6%, respectively. In terms of development depth, the development of UUS in Shanghai shows a more obvious characteristic of stratified use (Figure 1). At present, basement structures are generally buried within 30 m of the surface (Figure 2), tunnel projects are primarily located at depths of 20-40 m, and some building foundations extend to 30–50 m into bearing soil layers (Figure 3). As shown in Figure 2 and Figure 3, the underground space in the central urban area of Shanghai has been developed at a relatively high density. The volumetric distribution of shallow underground space utilization is illustrated in Figure 4. It can be observed that shallow and intermediate underground space development in central Shanghai exhibits a pattern of 'widespread utilization with localized saturation'. Along both sides of the Huangpu River, underground space utilization is particularly intensive, with many land parcels exhibiting development volumes exceeding 30.000 to 100.000 m^3 , some of which have reached a high level of development intensity. This trend indicates that the potential for further expansion in shallow and intermediate underground space is rapidly diminishing. New development projects are increasingly constrained by structural saturation, functional conflicts, and safety risks. Therefore, it is urgently necessary to extend development into deeper underground layers to achieve a more graded use of underground space resources and an optimized spatial-functional layout.

As the mid-shallow underground space becomes increasingly saturated, the construction of new linear infrastructure, such as rail transit lines and utility tunnels, facing growing spatial conflicts and engineering difficulties. Consequently, the demand for deep underground space development is emerging. According to the *Shanghai Master Plan (2017–2035)*, underground space deeper than 50 m is classified as “deep underground space” and is primarily reserved for key functional systems such as high-speed transportation, logistics distribution, stormwater regulation, and energy transmission (Figure 5). Shanghai has entered the initial stage of deep underground space development. Representative projects include the Suzhou Creek deep drainage and storage tunnel (pilot section), where the shield shaft excavation depth reaches nearly 60 m, diaphragm walls extend down to 103m -105 m, and tunnel sections are typically located at depths of 50m - 60 m. The hard X-ray free-electron laser facility features shaft depths of around 50 m and diaphragm walls extending to approximately 100 m. The Shanghai Yangtze River Tunnel and Bridge project reaches a maximum burial depth of 55 m beneath the riverbed. Compared with shallow and intermediate layers, deep underground space offers advantages such as greater integrity, minimal surface interference, strong enclosure, and substantial development potential, making it particularly suitable for accommodating critical infrastructure. For a megacity like Shanghai, the systematic development of deep underground space has become an urgent necessity, and evaluating its bearing capacity is a fundamental prerequisite to ensuring its safe, efficient, and sustainable utilization.

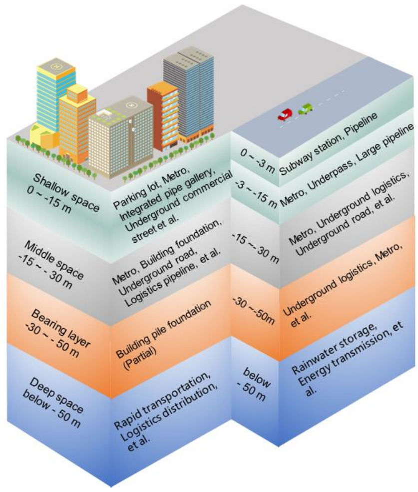


Figure 1. *Vertical stratified utilization of UUS in Shanghai*

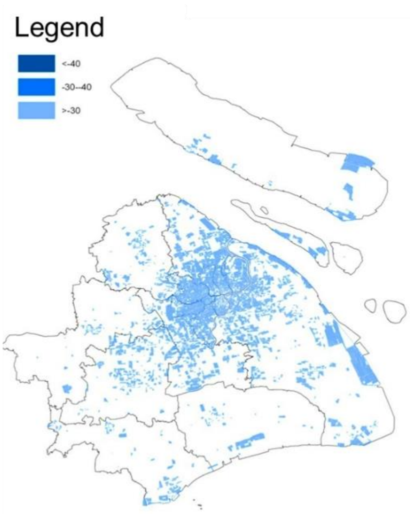


Figure 2. *Basement depth distribution in Shanghai*

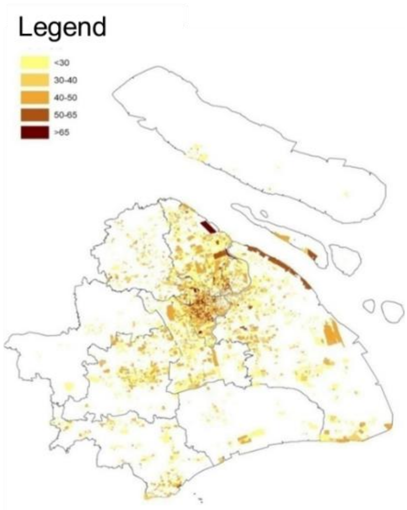


Figure 3. *Lepth of underground pile foundation in Shanghai*

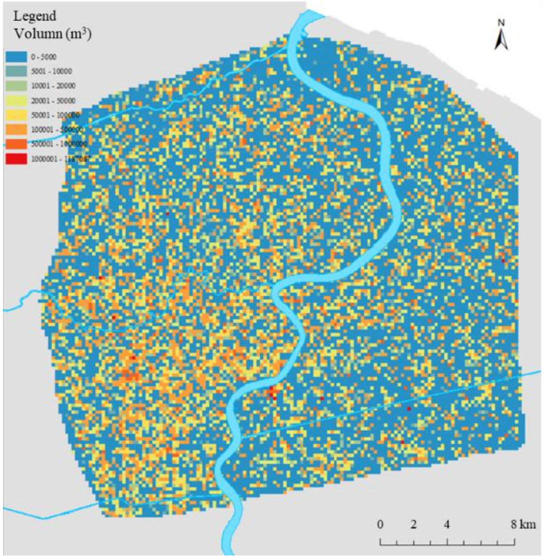


Figure 4. *Utilization volume of shallow and middle underground space in the central urban area of Shanghai*

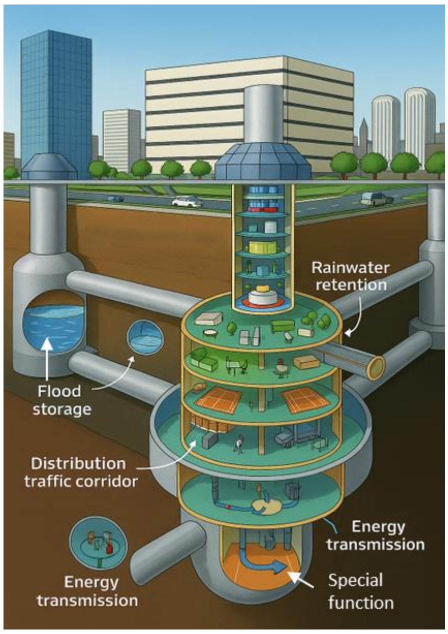


Figure 5. *Functional layout of DUS of Shanghai*

2.2. Characteristics of Deep Soil Strata in Shanghai

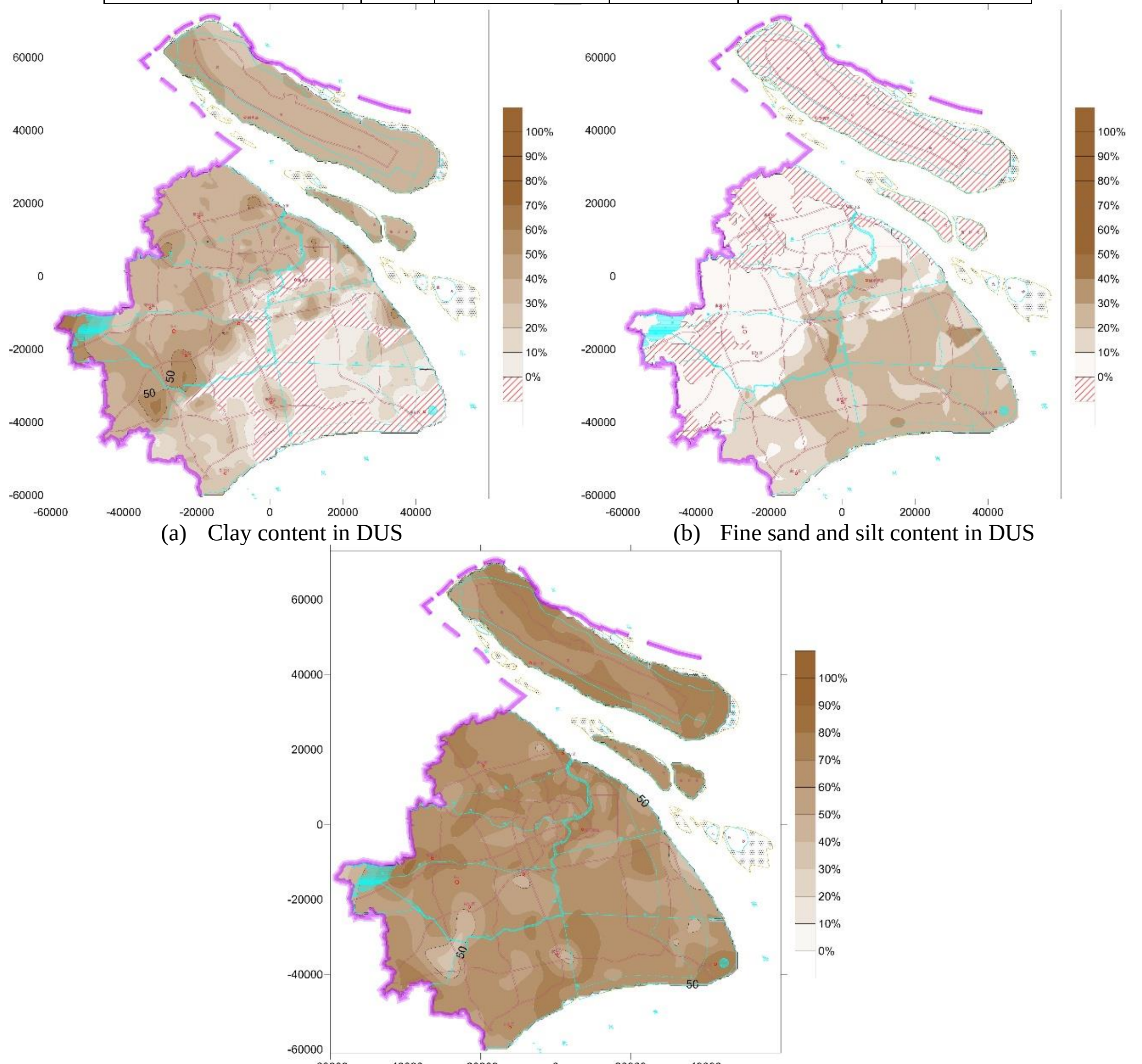
Shanghai is located on a deltaic alluvial plain and is representative of regions characterized by natural soft soil. The subsoil profile can be divided into 12 major soil layers, containing one phreatic aquifer, one micro-confined aquifer, and five confined aquifers. These layers are notable for their large cumulative thickness and abundant groundwater. The soil strata within the shallow to intermediate underground space primarily consist of soft clay and sandy soils, while those in the deep underground space are mainly composed of silty fine sand and sandy clay. The geological distribution of deep underground space (50m -100 m) in Shanghai is presented in Table 1.

As shown in Table 1 and Figure 6, medium to coarse sand accounts for approximately 64.69% of the deep strata, while clay makes up nearly one-third. The deep sandy layers are generally of low bearing capacity and moderate compressibility, with limited liquefaction potential. In contrast, deep clayey soils are prone to significant plastic deformation and consolidation settlement. The layer ⑧, a relatively thick clay stratum, is considered suitable for construction and may act as an effective barrier to the first and second confined aquifers. Laboratory testing has identified the layer ⑧ as overconsolidated clay, indicating favorable conditions for deep underground space development in areas where it is well developed.

Compared to shallow and intermediate strata, deep soils exhibit lower plasticity indices and liquid limits, fewer silt particles, and a higher proportion of clay particles. Except for layer ⑧$_1$, the deep soil layers mainly consist of plastic to stiff clays and medium-dense to dense silty soils and silts, characterized by high strength, good uniformity, relatively low compressibility, and strong bearing capacity. Overall, from the perspective of physical and mechanical soil properties, although deep underground development presents more engineering challenges than shallow development, the deep strata in coastal regions such as Shanghai remain suitable for underground space exploitation.

Table 1. *Geological conditions of deep underground space in Shanghai*

Geological layer	**No.**	**Top burial depth (m)**	**Thickness (m)**	**State or compaction**	**Distribution**
Gray clay with silty sand	⑧$_1$	40.0~60.0	6.0~30.0	Soft-Plastic to plastic	Partial absence
Gray silty clay interbedded with silty sand	⑧$_2$	50.0~60.0	10.0~20.0	Plastic or medium dense	Partial absence
Grayish-blue fine sand with clay	⑨$_1$	65.0~77.0	5.0~8.0	Medium dense to dense	Stable distribution
Grayish-blue fine silty sand with medium sand	⑨$_2$	75~81.0	5.0~10.0	Dense	Stable distribution
Blue-gray or brown-gray clay	⑩	86.0~101.0	4.0~10.0	Hard-Plastic	Extensive distribution
Grayish-blue fine silty sand	⑪	88.0~101.0	10.0~30.0	Dense	Extensive distribution



(a) Clay content in DUS

(b) Fine sand and silt content in DUS

(c) Medium - Coarse Sand Content in DUS

Figure 6. *Proportions of different soil types in DUS of Shanghai*

3. ANALYSIS OF INFLUENCING FACTORS OF THE DUS BEARING CAPACITY

Under the current level of engineering technology and safety regulations, the bearing capacity of deep underground space (DUS) is defined as the maximum capacity of deep subsurface strata in a specific area to accommodate various underground space functions. This capacity not only reflects the sustainable development potential of underground space resources but also represents the critical threshold for ensuring urban operational safety and coordinated resource utilization. It is a complex quantitative system influenced by the coupling of multiple factors. The core of DUS bearing capacity evaluation lies in the comprehensive assessment of the quantity, quality, suitability, and limiting factors of deep underground space resources. Urban underground resources include not only underground space itself but also groundwater, geological materials, and underground geothermal energy(Li et al., 2016; Attard et al., 2017; Li et al., 2018). Therefore, this evaluation process must account for multiple dimensions, such as regional geological structure, geotechnical conditions, hydrogeological characteristics, environmental sensitivity, and the existing state of surface and shallow underground space development. Notably, deep underground space interacts significantly with other underground resources. On one hand, deep excavation and construction may lead to changes in groundwater levels, thermal field disturbances, or the destabilization of geotechnical strata. On the other hand, factors such as groundwater abundance, geotechnical strength, and the distribution of geothermal energy may in turn constrain the feasibility of deep space development. Shanghai has a low frequency and low intensity of seismic activity, and the overall stability of the region is favorable. This section will analyze the key influencing factors of DUS bearing capacity in Shanghai and establish a comprehensive evaluation index framework accordingly.

3.1. Engineering geology condition

Engineering geological conditions are a fundamental factor influencing the development and utilization of underground space. For deep underground space, its bearing capacity primarily depends on the depth to bedrock, the thickness of clay layers, soil uniformity, and the composition of stratigraphic sequences.

Shanghai is covered by a thick Quaternary layer, with the bedrock surface overlain by deposits ranging from 150 to 350 meters in thickness. Bedrock outcrops are found in the western and southwestern regions. In the central urban area, the bedrock is generally buried deeper than 160 meters, though exceptions exist—such as in parts of Xuhui District, where the bedrock rises significantly and can be as shallow as 60 meters below ground surface. Therefore, particular attention must be paid to bedrock depth during deep underground development.

In the main regions targeted for deep underground space development in Shanghai, the strata are primarily composed of silty fine sand and sandy clay. Due to the low permeability of clay, compressive deformation under long-term loading continues to accumulate. In addition, heterogeneity in regional geological conditions can lead to differential settlement of soil layers. Excessive differential settlement may result in longitudinal deformation or excessive curvature of deep tunnels, leading to segmental damage of the tunnel lining. Furthermore, the absence of the ⑧ layer in some areas significantly increases soil non-uniformity, which may adversely affect the overall stability of underground structures.

Therefore, in the context of Shanghai, stratigraphic composition, soft soil thickness, and soil uniformity are critical factors affecting the bearing capacity of deep underground space. A comprehensive evaluation and proper mitigation of these factors must be conducted prior to development.

3.2. Geotechnical characteristics

Geotechnical characteristics have a direct influence on the ease of excavation and the stability of the surrounding rock. Therefore, geotechnical stability is one of the important influencing factors for the carrying capacity of underground spaces. The geotechnical properties that influence the bearing capacity of underground space primarily include strength characteristics, deformation behavior, unloading response, and permeability. Under otherwise identical conditions, stronger soil or rock masses generally correspond to greater usable underground space capacity within a given area. Strength indicators such as cohesion, internal friction angle, and the standard value of bearing capacity are key parameters for evaluating geotechnical stability. The compression modulus is an important parameter reflecting the soil's resistance to deformation—higher values indicate greater resistance to external disturbance.

Deep underground space development typically causes significant disturbance to the surrounding soil, substantially altering the in-situ stress state. The coefficient of earth pressure at rest (K_0) helps characterize the unloading behavior of deep soils and plays a critical role in understanding their deformation mechanisms. In deep strata, stress paths are dominated by unloading or unloading followed by reloading, with mechanical behavior differing significantly from shallow layers. For example, under consolidation pressures ranging from 6 to 10 MPa, increased stress leads to enhanced microstructural anisotropy in clay, which is macroscopically reflected by large variations in the K value.

In addition, the permeability coefficient is a key parameter for evaluating the waterproofing capacity of geotechnical layers. Higher permeability indicates weaker water resistance. Severe groundwater seepage can destabilize surrounding rock masses and soil structures, compromising excavation safety and ultimately reducing the bearing capacity of the underground space.

3.3. Hydrogeology

Shanghai has abundant groundwater with a high water table. The groundwater aquifers within the range of 0 to 100 meters below the surface are sequentially classified as phreatic, micro-confined, and confined aquifers, with the first and second confined aquifers (I and II) being closely related to the development and utilization of deep underground space, as shown in Figure 7.The first confined aquifer corresponds to Layer ⑦ and lies above Layer ⑧. It is widely distributed and, influenced by sedimentary environments and ancient river channel cutting, shows significant variation in depth, thickness, and water yield. The second confined aquifer corresponds to Layer ⑨, and is widely distributed and stable. It is one of the most permeable and water-rich aquifers in the Shanghai area, with high artesian pressure.

There is a close hydraulic connection between the various confined aquifers in the region. The first and second confined aquifers are connected in areas where Layer ⑧ is absent; the second confined aquifer is locally connected with the third confined aquifer (at depths of 110–120 meters); in some areas of the central urban district, such as the Lujiazui area, all three confined aquifers are interconnected.

Artesian water poses significant challenges to the development and utilization of deep underground space in Shanghai. First, the first and second confined aquifers are deep sand layers, resulting in high shield tunneling resistance. Second, the artesian pressure in these aquifers is high, which can easily lead to blowouts and sand flows during excavation. Finally, in areas where confined aquifers are interconnected, improper dewatering during construction can cause widespread ground subsidence.

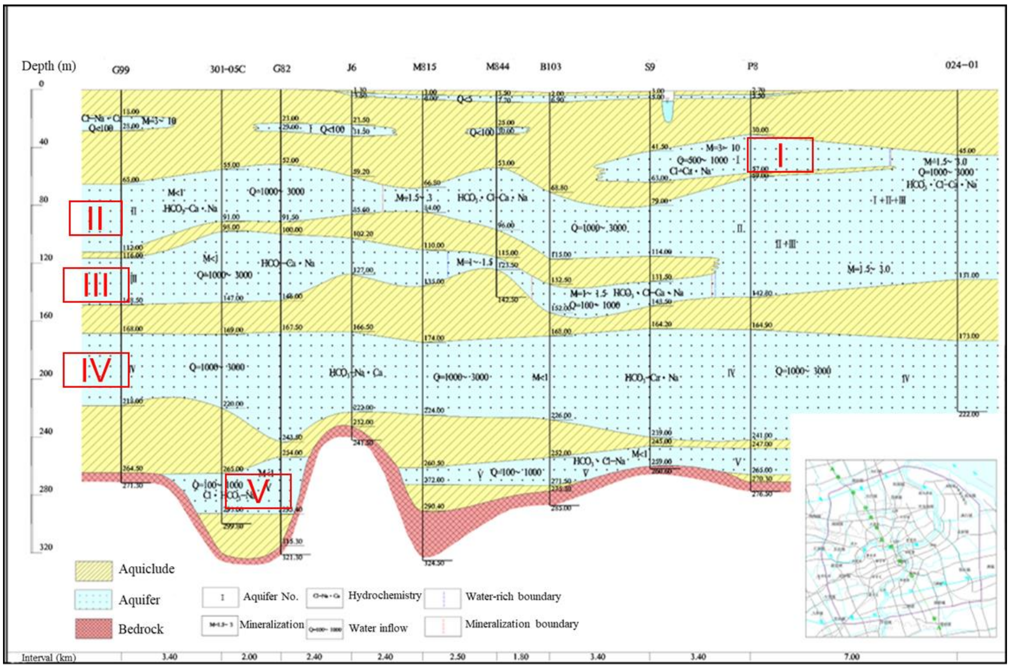


Figure 7. *Typical Hydrogeological Profile of Shanghai*

3.4. Environmental geology

According to the unique geological and environmental conditions of Shanghai, the main environmental and geological problems that occur during the development and utilisation of underground space are the following: ground subsidence, sand liquefaction, and gas escape. However, the impact of thermal-hydrological mechanical-chemical (THMC) coupling on the development and utilisation of underground space has been less considered.

3.4.1. Ground subsidence

Ground subsidence caused by the environmental effects of underground space development has become one of the major environmental geological challenges in Shanghai. Although long-term control measures such as zoning management and stratified regulation have yielded positive results of keeping the overall subsidence trend relatively stable, significant localized uneven settlement remains. This is particularly relevant to the construction of deep underground space (DUS), which induces more complex and extensive disturbance to the subsurface strata.

During DUS construction, large-scale excavation and the associated engineering activities often disturb deep soil layers, causing consolidation deformation. To facilitate safe excavation, it is usually necessary to perform deep dewatering operations to lower the artesian water pressure around the foundation pit. However, such depressurization can lead to a significant drawdown of the confined groundwater levels outside the excavation zone. When the target aquifer cannot be fully isolated, the resulting hydraulic imbalance may trigger widespread ground settlement, especially differential settlement within the dewatering-induced subsidence funnel. This not only threatens the structural safety of deep underground projects but also poses risks to existing surface structures and shallow to intermediate underground spaces. Therefore, ground subsidence, particularly that induced by groundwater drawdown and soil disturbance, must be considered a critical factor in the evaluation of DUS bearing capacity.

3.4.2. Sand Liquefaction

Shanghai has a high water level, and the chalk and sandy chalk layers within the influence of underground space development generally have the characteristics of sandy soil seepage liquefaction. There have been many engineering accidents due to s and liquefaction problems during the construction of underground projects in the Shanghai area.

3.4.3. Deep natural gas escape

Natural gas is widely developed within the Quaternary strata in the Shanghai area and can be categorized into three gas-bearing reservoir systems. The development of deep underground space is mainly affected by the second and third gas-bearing layers, typically buried at depths of 30 – 50 m and 50 – 70 m, respectively. Although these layers have a relatively limited distribution, they are characterized by high pressure and large gas flow rates. If encountered during excavation, the sudden release of gas may pose serious safety risks to personnel, cause instability in the surrounding soil, and even lead to the danger of explosion.

3.4.4. Coupling of multiphysical fields in the deep underground Environment

In deep underground space environments, the geological system is composed not only of rock, soil, and groundwater, but also of interrelated thermal, hydraulic, mechanical, and chemical (THMC) fields. In Shanghai, the deep subsurface (typically below 50 m) features water-rich, low-permeability soils such as silty sand and sandy clay, where confined aquifers are widely distributed. These strata are subject to elevated geostress, temperature gradients, and mineralized groundwater with active geochemical interactions.

The development and utilization of deep underground space inevitably disturb the original equilibrium of the subsurface system. Excavation and dewatering lead to stress redistribution, which in turn induces changes in pore water pressure, groundwater seepage, and geochemical reactions. The confined groundwater exhibits higher pressure and deeper flow paths, making its hydromechanical coupling effects more pronounced than in shallow layers. Temperature gradients at greater depths also intensify thermally induced deformation, especially under long-term loading or structural heat emissions.

The THMC coupling effect in deep strata is thus characterized by enhanced mechanical sensitivity, delayed consolidation behavior, and complex water – rock – heat – stress interactions. These interdependencies alter the displacement and strength responses of the geotechnical body, influencing not only construction safety but also the long-term bearing capacity of the surrounding formations. Therefore, it is essential to incorporate THMC coupling mechanisms into the assessment and planning of deep underground space development, particularly in soft-soil megacities like Shanghai.

3.5. Ground and underground space status

n the development of deep underground space (typically below 50 m), the current utilization of both surface and underground space constitutes a key factor influencing its bearing capacity. Unlike shallow and intermediate underground spaces, deep space is less directly affected by surface usage conditions, yet certain constraints still exist.

(1) Influence of ground space utilization

The surface space in urban areas consists of high-rise buildings, heritage sites, historical landmarks, public squares, green spaces, and roads. In densely built-up zones, the vertical load transferred by high-rise structures may affect the stability of underlying strata, necessitating stability assessments for any deep-level excavation. Areas with high floor area ratios (FAR) also tend to have dense underground infrastructure, which limits construction access. Moreover, cultural heritage sites, conservation zones, and critical infrastructure are often associated with protection layers that restrict vertical development. Although deep underground space lies below most of these influence zones, the potential for indirect disturbance—such as vibration, groundwater changes, or settlement, must still be evaluated. Thus, surface utilization impacts deep underground space development primarily through protection requirements and structural load effects.

(2) Influence of underground space utilization

By contrast, the bearing capacity of deep underground space is more directly constrained by the existing use of shallow and intermediate underground layers. Structures such as metro tunnels, underground commercial facilities, utility corridors, and pipelines present physical barriers to deeper development. Their structural extents, buffer zones, and operational safety requirements must all be accounted for. In addition, some areas have been designated as underground restricted development zones, such as heritage tunnels, key pipeline protection corridors, and groundwater source protection zones, where new deep excavation is prohibited or strictly controlled.

Given these conditions, the assessment of deep underground space bearing capacity requires careful delineation of developable zones, interference zones, and reserved protection layers based on existing surface and subsurface usage. Compared with shallow space development—which is more sensitive to surface occupation—deep underground development places greater emphasis on compatibility with existing subsurface systems and hierarchical space utilization. This reflects the need for integrated vertical planning and coordinated management of underground resources.

4. FRAMEWORK OF AN EVALUATION INDEX SYSTEM FOR THE DUS BEARING CAPACITY

Taking into account the complexity of deep underground space development and the characteristics of multi-source coupling, this study establishes a comprehensive evaluation system for bearing capacity based on five primary categories of indicators: engineering geology, geotechnical characteristics, hydrogeology, environmental geology, and current space utilization(including ground space and underground space), as shown in Figure 8. The system aims to comprehensively reflect the physical and mechanical properties of strata, environmental sensitivity, and engineering suitability, serving as a fundamental basis for assessing regional development suitability and conducting quantitative evaluations.

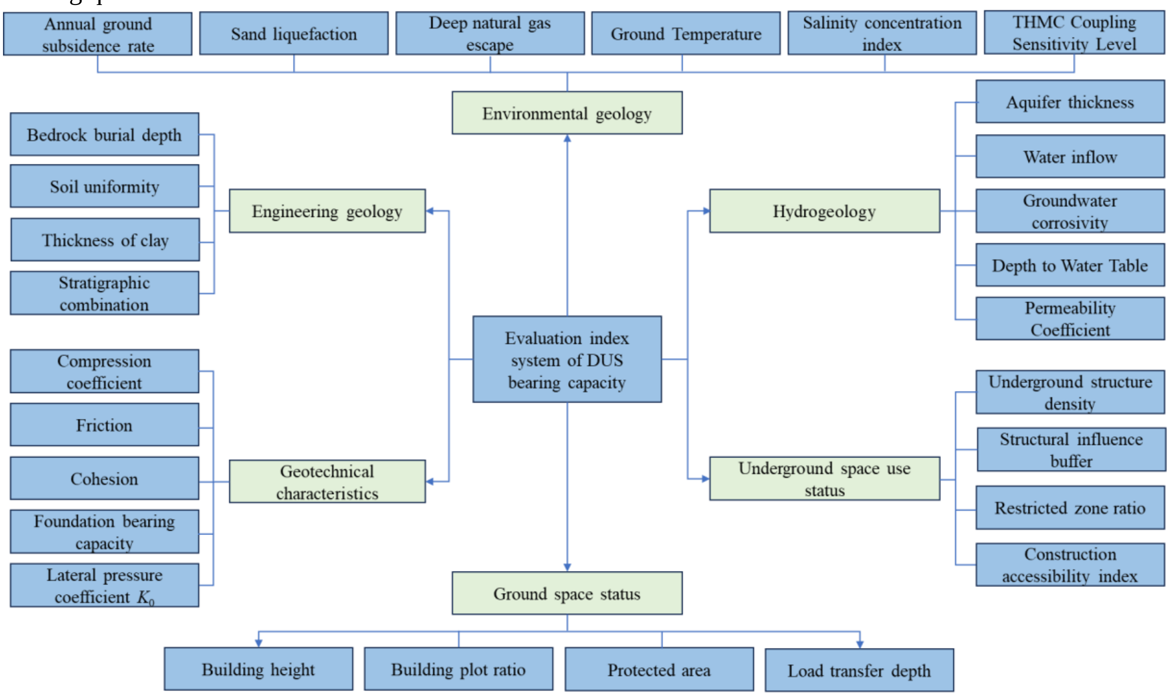


Figure 8. *Evaluation index system framework of the DUS bearing capacity*

5. CONCLUSIONS

This study addresses the critical need for evaluating the carrying capacity of deep underground space (DUS) in megacities, focusing on Shanghai as a representative case. The city's unique coastal soft soil conditions, thick Quaternary strata, and multi-aquifer system present both challenges and opportunities for DUS development. Through detailed analysis of geological, hydrogeological, and environmental factors, key constraints such as bedrock depth, soft soil thickness, confined aquifer pressure, and THMC coupling effects were identified. In addition, the spatial utilization status, both above and below ground was incorporated to reflect realistic development limitations. A comprehensive evaluation index system was constructed, integrating five dimensions: engineering geology, geotechnical characteristics, hydrogeology, environmental geology, and current space utilization. The system allows for structured, multi-factor assessment of DUS carrying capacity. The study confirms that deep development is becoming an inevitable direction for megacities like Shanghai as shallow resources near saturation. A scientific assessment of DUS carrying capacity is therefore essential for safe, efficient, and sustainable underground development. The findings lay the foundation for future quantitative modeling of DUS bearing capacity.

Moving forward, the proposed index system can be further refined through quantitative modeling, spatial data integration, and multi-criteria decision analysis (MCDA), enabling region-specific evaluation of deep underground space carrying capacity under varying geological and urban conditions.

6. ACKNOWLEDGMENTS

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7. REFRENCES

[1] Admiraal, H., & Cornaro, A. (2020). Future cities, resilient cities – The role of underground space in achieving urban resilience. *Underground Space*, *5*(3), 223–228. https://doi.org/10.1016/j.undsp.2019.02.001

[2] Attard, G., Rossier, Y., Winiarski, T., & Eisenlohr, L. (2017). Urban underground development confronted by the challenges of groundwater resources: Guidelines dedicated to the construction of underground structures in urban aquifers. *Land Use Policy*, *64*, 461–469. https://doi.org/10.1016/j.landusepol.2017.03.015

[3] Bobylev, N. (2009). Mainstreaming sustainable development into a city's Master plan: A case of Urban Underground Space use. *Land Use Policy*, *26*(4), 1128–1137. https://doi.org/10.1016/j.landusepol.2009.02.003

[4] Bobylev, N. (2016). Underground space as an urban indicator: Measuring use of subsurface. *Tunnelling and Underground Space Technology*, *55*, 40–51. https://doi.org/10.1016/j.tust.2015.10.024

[5] Chen, Z.L., Chen, J.Y., Liu, H., Zhang, Z.F. (2018). Present status and development trends of underground space in Chinese cities: Evaluation and analysis. *Tunnelling and Underground Space Technology*, *71*, 253–270. https://doi.org/10.1016/j.tust.2017.08.027

[6] He, J., Zhou, Y.X., Zheng, G.S., Wang, J.M., Liu, Y. (2020). Research on the Geological Suitability Evaluation System of Underground Space Resource Utilization in Beijing. *Chinese Journal of Underground Space and Engineering*, *16*(4), 955-966.

[7] He, L., Song, Y., Dai, S., & Durbak, K. (2012). Quantitative research on the capacity of urban underground space – The case of Shanghai, China. *Tunnelling and Underground Space Technology*, *32*, 168–179. https://doi.org/10.1016/j.tust.2012.06.008

[8] Kishii, T. (2016). Utilization of underground space in Japan. *Tunnelling and Underground Space Technology*, *55*, 320–323. https://doi.org/10.1016/j.tust.2015.12.007

[9] Lai, Y., Wang, Y., Cheng, J., Chen, X., & Liu, Q. (2023). Review of constraints and critical success factors of developing urban underground space. *Underground Space*, *12*, 137–155. https://doi.org/10.1016/j.undsp.2023.03.001

[10] Li, H. Q., Fan, Y. Q., & Yu, M. J. (2018). Deep Shanghai project – A strategy of infrastructure integration for megacities. *Tunnelling and Underground Space Technology*, *81*, 547–567. https://doi.org/10.1016/j.tust.2018.08.008

[11] Li, X., Li, C., Parriaux, A., Wu, W., Li, H., Sun, L., & Liu, C. (2016). Multiple resources and their sustainable development in Urban Underground Space. *Tunnelling and Underground Space Technology*, *55*, 59–66. https://doi.org/10.1016/j.tust.2016.02.003

[12] Li, Y.Y., Cai, X.K., Wang, Y.H. (2025). Challenges and Strategies of Urban Deep Underground Space Development in China. *Chinese Journal of Underground Space and Engineering*, *21*(1), 1-15, 69.

[13] Liu, Y., Zhu, L.C. (2020). Current Status and Future Perspectives of Urban Underground Space Development in Shanghai, *Chinese Journal of Underground Space and Engineering,* 40(7), 941-952. https://doi.org/10.20174/j.JUSE.2025.01.01
[14] Lu, Z., Wu, L., Zhuang, X., & Rabczuk, T. (2016). Quantitative assessment of engineering geological suitability for multilayer Urban Underground Space. *Tunnelling and Underground Space Technology*, *59*, 65–76. https://doi.org/10.1016/j.tust.2016.06.003
[15] Mukhtar, A., Yusoff, M. Z., & Ng, K. C. (2019). The potential influence of building optimization and passive design strategies on natural ventilation systems in underground buildings: The state of the art. *Tunnelling and Underground Space Technology*, *92*, 103065. https://doi.org/10.1016/j.tust.2019.103065
[16] Peng, J., & Peng, F.L. (2018a). A GIS-based evaluation method of underground space resources for urban spatial planning: Part 1 methodology. *Tunnelling and Underground Space Technology*, *74*, 82–95. https://doi.org/10.1016/j.tust.2018.01.002
[17] Peng, J., & Peng, F.L. (2018b). A GIS-based evaluation method of underground space resources for urban spatial planning: Part 2 application. *Tunnelling and Underground Space Technology*, *77*, 142–165. https://doi.org/10.1016/j.tust.2018.03.013
[18] Price, S. J., Terrington, R. L., Busby, J., Bricker, S., & Berry, T. (2018). 3D ground-use optimisation for sustainable urban development planning: A case-study from Earls Court, London, UK. *Tunnelling and Underground Space Technology*, *81*, 144–164. https://doi.org/10.1016/j.tust.2018.06.025
[19] Qiao, Y.K., Peng, F.L., Wu, X.L., & Luan, Y.P. (2022). Visualization and spatial analysis of socio-environmental externalities of urban underground space use: Part 1 positive externalities. *Tunnelling and Underground Space Technology*, *121*, 104325. https://doi.org/10.1016/j.tust.2021.104325
[20] Sterling, R., Admiraal, H., Bobylev, N., Parker, H., Godard, J.P., Vähäaho, I., Rogers, C. D. F., Shi, X., & Hanamura, T. (2012). Sustainability issues for underground space in urban areas. *Proceedings of the Institution of Civil Engineers - Urban Design and Planning*, *165*(4), 241–254. https://doi.org/10.1680/udap.10.00020
[21] Zhang, Y., Zhu, J., Liao, Z., Guo, J., Xie, H., & Peng, Q. (2021). An intelligent planning model for the development and utilization of urban underground space with an application to the Luohu District in Shenzhen. *Tunnelling and Underground Space Technology*, *112*, 103933. https://doi.org/10.1016/j.tust.2021.103933
[22] Zhou, C., Su, Y., He, L., Peng, L., Zhang, Y., Wu, G., & Kiong Soh, C. (2024). An intelligent resilience evaluation model for the development of urban underground space with safety concern of surrounding existing built environment. *Tunnelling and Underground Space Technology*, *149*, 105783. https://doi.org/10.1016/j.tust.2024.105783