New planning and design concept for urban underground spaces based on geo-environmental factors

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Abstract. As the urbanization in China advances, urban underground spaces are vigorously developed through large-scale projects. However, the development of underground spaces often proceeds without prior scientific planning and design. City planners who fail to consider geo-environmental factors tend to design nonholistic blueprints that may cause serious problems. The development of an underground space is irreversible because underground resources are currently deemed highly valuable. Therefore, scientific planning must be conducted before the construction and launch of underground space projects. This study adopts a new concept of underground space planning and design and analyzes unfavorable geo-environmental factors, such as sand liquefaction and soft soil, which affect the development of underground spaces. The development mode of the underground space suitable for the geological environment in the study area is proposed. Based on the new concept of planning and design, this work considers a case study in Guangdong Province as a reference for the development mode, depth, and function of underground space in the study area. The findings of this study provide some new planning and design ideas for the development and utilization of underground spaces.

1 Introduction
Urban underground resources are precious. The development of an underground space requires prior scientific planning and design. However, city planners often fail to realize the importance of geo-environmental factors when planning the development of underground spaces. Unfavorable geo-environmental factors hinder the development of underground spaces and result in massive engineering costs and even site relocation. These drawbacks in turn affect the safe operation of underground projects in the future. Importantly, unreasonable development of underground spaces also causes resource wastage and damage to the geological environment. The urban geological condition is fragile, sensitive, and irreversible. During underground space development, the urban geological
environment is highly vulnerable to destruction. Once the geological environment is disturbed, fully recovering it becomes difficult. Therefore, geo-environmental factors must be considered in underground space planning. Hulme and Zhao (1999) considered the geological, hydrological, environmental, psychological, ground development, social, economic, and political factors as evaluation factors to study the planning and location of an underground space in Singapore. Based on the analysis of the geo-environmental factors as well as the demand factors of the study area, the present study proposes some guidelines for underground space planning.

2 Research methods
This work starts from the perspective of urban planning through the analysis of population density, land use nature, rail transit, and other influencing factors. Then, the regional demand level of underground space development is divided. The geo-environmental factors affecting the development of the underground space in the study area are subsequently analyzed. The interaction mechanism between each influencing factor and the underground space is also discussed. Finally, the study proposes a suitable development mode for the underground space in the study area, with a focus on the development depth, function combination, and other aspects of the underground space.

Figure 1. Research methods

3 Study area
Located in the Pearl River Delta urban agglomeration, the Marina Bay New Area is a representative cooperation platform for the Guangdong–Hong Kong–Macao Greater Bay Area, a pilot development area for the Guangdong–Hong Kong–Macao Greater Bay Area, and a core platform for the Guangzhou–Shenzhen Science and Technology Innovation Corridor. The planned area stretches from the Maozhou River in the east to the junction of Weiyuan island and Shatian town in the west, to the Yanjiang Expressway in the north, and to the Pearl River Estuary in the south. The planned area measures 84.1 km², of which the current land area is 51.8 km² and the planned land area is 60.3 km² after project completion.
This study delineates the TOD of Marina Bay station as the key study area to examine the factors and their effects. On the basis of the planning and design concept, a regional development plan of the underground space is deliberately formulated. The vacant land will be blanketed with new stations and other facilities on the surface and is expected to be ready for remarkable underground works. Therefore, suitable planning should be conducted on such a special TOD area.

4 Analysis of underground space development demand

This study analyzes the demand for underground space development in the study area from the aspects of population density, location conditions, rail transit, and land use nature. According to the influence of these factors on underground space demand, a quantitative analysis of each factor index is performed. Based on the analytic hierarchy process (AHP), the demand grade of the underground space is divided.

4.1 Population density

Population density is an important index to characterize the degree of urban space and other resources. The size of population density determines the intensity of the demand for human survival resources in the unit land area of a given city, as well as the amount of space resources per capita, the amount of traffic resources per capita, and the per capita municipal facility ownership. In the context of compact urban development, the greater the population density is, the higher the potential value of underground space resources and the greater the demand for underground space will be.

According to the prediction of the future population scale in the urban master plan of Marina Bay New Area of Dongguan City (2018–2035), the urban population density of Marina Bay New Area in 2035 will be approximately 5,945 people/km² and the urban center population density is expected to be more than 10,000 people/km².

Relevant studies have shown that population density directly affects the shortage of urban space resources. Moreover, a strong linear positive correlation exists between the intensity of underground

![Figure 2. Location plan](image-url)
space development and the density of permanent population. Compared with the population density of domestic cities, the population density of Marina Bay New Area is projected to reach an extremely high level in 2035. In the urban center in particular, the demand for underground space is expected to soar. The area is divided into four levels on the basis of the principle stating that the greater the population density is, the higher the demand for underground space is.

4.2. Land use function

The construction land of Marina Bay New Area is set to 39.47 km² in 2020 and 43.75 km² in 2035.

| Land use type                                      | Area (km²) | Proportion |
|---------------------------------------------------|------------|------------|
| Residential land                                  | 8.54       | 19.52%     |
| Land for public service facilities                | 5.92       | 13.52%     |
| Land for transportation facilities                | 9.09       | 20.77%     |
| Comprehensive land use (commerce, culture, and entertainment) | 6.01 | 13.73% |
| Land for commercial service facilities            | 2.30       | 5.25%      |
| Greenland                                         | 8.44       | 19.29%     |
| Others                                            | 3.45       | 7.92%      |

The level of demand for underground space development varies based on the nature of land use on the ground. The demand for underground space development is often high in the commercial land areas and areas undergoing high-intensity surface development. The levels of demand for underground space development are classified based on different land use properties.

4.3. Rail transit

According to the urban master plan and traffic plan, multiple subway lines and railways will pass through the study area. On the basis of domestic and foreign cases, the plots around the rail transit station are deemed suitable for large-scale joint development above and below the ground. The area is divided into three zone levels according to the distance from the rail transit station. The classification is based on the principle that the closer a zone is to the rail transit station, the higher is its demand for underground space.
Figure 3. Planning of rail transit stations in Marina Bay New Area

4.4. Summary

Based on the analysis of population density, land use function, rail transit, and other factors, the underground space demand areas in the study area are divided into high, medium–high, medium–low demand areas and proposed reserve area.

Figure 4. Classification map of underground space demand in Marina Bay New Area

5 Analysis of geo-environmental factors affecting the development of underground space

The main geological factors affecting the development of the underground space in the study area include fault, sand liquefaction, and soft soil.

5.1. Fault

Structural stability is the basis of the stability and safety of an underground space structure system. The main faults in the study area are the Shiziyang fault bundle and Nansha Dongguan fault zone. As for the basic intensity of the study area, Marina Bay New Area is located in the seismic fortification intensity zone of 7 degree, and the basic seismic acceleration design value is 0.10 g. According to drilling data, cataclastic granite and tectonic breccia can be found in many boreholes near the fault zone, and they indicate the buried depth of the fault fracture zone. Given its poor rock integrity and hydraulic conductivity, the fault fracture zone may adversely affect the development of the underground space.
According to drilling data, the buried depth of cataclastic rocks and tectonic breccia in the fault area, which indicate the location of the fault fracture zone, is in the range of 60–100 m. Hence, the buried depth of the fault fracture zone is assumed to be more than 60 m. The fault fracture zone has little influence on the development of the underground space within 50 m of the shallow and sub shallow underground.

Fault avoidance is based on an important theoretical assumption: the surface rupture of future earthquakes is most likely to occur along the faults that have occurred in the past. Therefore, a certain width of influence zone should be drawn on both sides of the fault. The figure shows that the main faults affecting the engineering construction in the study area are the Shiziyang fault bundle and the six main faults in the Nansha Dongguan fault zone. According to a previous study on the activity of the faults in this area, the faults and hidden faults in the study area are still active and should thus be considered in the construction of the underground space.

5.2. Sand liquefaction
When pore water pressure is excessively high, the sand at the bottom of an underground structure becomes liquefied. When the underground structure is located in an easily liquefied sand layer, the shear strength of the soil decreases, leading to the uplift or subsidence of the underground structure.

The liquefiable sand in the study area is mainly loose and has slightly dense saturated silt, fine sand, silty fine sand, and slightly dense silt in Holocene and Pleistocene. The buried depth of liquefied soil in the study area is 5–20 m, and the thickness of most areas is less than 5 m.
The impact of sand liquefaction on the development of the underground space is evaluated and regionalized in this work on the basis of the buried depth and thickness of the liquefied soil in the study area.

(1) For the area with a buried depth of 5–10 m, the thickness of liquefied soil is less than 5 m. For the shallow underground space, liquefied soil is basically located above or around the underground structure. The seismic subsidence caused by sand liquefaction has little impact on the underground structure and on the operation and maintenance safety of the shallow underground space. The difficulty of underground space development is also minimal.

(2) For the area with a buried depth of 10–20 m, the thickness of liquefied soil is less than 5 m. For the shallow underground space, although the underground structure is located in a liquefied soil layer, the thickness of the liquefied soil below it is small. The liquefaction of sand reduces the shear strength of the liquefiable soil layer at the bottom of structures. This condition leads to the instability and damage of underground structures. Nonetheless, the impact is minimal, and the difficulty of underground space development is moderate.
5.3. Soft soil

Mucky soft soil is widely distributed in the research area. Its nature is weak, and it features high water content, low strength, high compressibility, and other adverse engineering characteristics that greatly influence the development and utilization of the underground space. The depth and thickness of the soft soil layer are important for the suitability of underground space development. For instance, deep soft soil is unfavorable to the development of underground space. The average water content and compression coefficient of the soft soil are 60.2% and 1.42 MPa$^{-1}$, respectively; hence, the engineering properties are weak. The buried depth of the soft soil floor is generally 5–25 m underground, spanning the shallow and sub shallow underground space. The thickness of the soft soil layer is relatively thick in the range of 0–22 m, which characterizes medium thick soft soil that results in a large settlement. The influence degree of soft soil on the development of the shallow underground space is divided according to the buried depth and thickness of the shallow (0–15 m) soft soil.

(1) For the area with soft soil thickness less than 5 m, the influence of soft soil on the development of the underground space mainly lies in the stability of the foundation pit excavation and soft soil settlement. Hence, underground space development is difficult.

(2) For the area with soft soil thickness greater than 5 m, the influence of soft soil on underground space development mainly lies in the stability of the foundation pit excavation, soft soil settlement, and insufficient bearing capacity of soft soil. Developing an underground space in this soft soil area is difficult.
6. Guidelines for underground space planning and design

6.1. Depth of underground space development

On the basis of the analysis of the demand factors and geo-environmental factors, the TOD urban center area formed by the Marina Bay station is selected as the key area of underground space research, and the suitable depth of underground space development in the study area is proposed. Under the geological environment conditions, such as fault, sand liquefaction, and soft soil distribution in the study area, the soft soil in the shallow underground space area (0–15 m) is widely distributed and relatively thick, and the liquefied soil affects a part of the area 10 m underground. Therefore, foundation treatment is required when the shallow (0–15 m) underground project is developed; the project will incur high engineering costs and exhibit high development difficulty. From the perspective of engineering economy and improving the utilization efficiency of underground space, the underground space development in important zones in the area should be carried out mainly in the sub shallow layer, and the development depth should be between 15 and 30 m. In this way, the underground engineering development can pass through the soft soil layer and liquefied layer.

Considering the previous demand analysis, this study puts forward the following planning guidelines for the depth of underground space development in this area. The underground development of roads and residential land is mainly shallow (underground, 1–2 floors), the underground commercial land is mainly sub shallow (underground, 3–4 floors), and the comprehensive development zone around the hub and station business area and subway station can be developed to more than 4 floors underground.
6.2. **Underground space development function**

In the vicinity of rail stations and important areas, the underground space should be developed and designed in layers. The traffic, municipal, parking, and other functions should be underground. The comprehensive functions should be developed and utilized in layers to improve the utilization efficiency of the underground space. The conditions of reserved connectivity when the underground space is developed in stages need to be considered to realize the multifunctional, comprehensive, layered development of the underground space.

On the basis of the previous analysis and regional urban planning, the following planning guidelines are proposed for various functional underground spaces in key areas. For the central axis plot in front of the Marina Bay station and around the subway station, the underground space should be developed with multiple functions. The underground pedestrian passageway should be arranged in combination with the traffic function on the first and second floors of the subway station. The underground commercial, cultural, and public entertainment functions should be integrated to create a regional underground pedestrian street. The underground parking function should be arranged according to the ground construction and public parking demand. The underground utility tunnel should be situated under the main road to meet the needs of urban municipal pipelines. In important traffic road sections, the underground tunnel and utility tunnel should be built in layers to solve ground traffic congestion. For nonconstruction land areas, such as agricultural and forestry lands, the underground space should be protected to reserve space for major infrastructure in the future.
Figure 10. Function plan of underground space development

7. Conclusion
Based on the development and utilization of the underground space in Marina Bay New Area, this study proposes a planning and design concept that combines demand and geo-environmental factors. The demand grades of the underground space in different zones are predicted through comprehensive analyses of population density, land use properties, and rail transit in the study area. Moreover, the influence of geo-environmental factors, such as fault, sand liquefaction, and soft soil, on the underground space development is studied. Geological factors affect the depth of underground space development. According to the demand prediction and analyses of geo-environmental factors, this study proposes the reasonable depth and function of the underground space in the study area. The findings of this work provide new planning and design ideas for the development and utilization of underground spaces.

8. References
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