Research on the Stable Region Division of Urban Underground Space Development

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Abstract. Based on giving full play to the self-stabilization ability of surrounding rock, this paper puts forward the concept, ideas and research methods of stable region division of urban underground space development. Then, the stable region division is systematically studied in the single stratum and the composite strata of upper soil and lower rock under different thickness of overlying soft soil stratum and different excavation span. It is pointed out that the larger the thickness of soft soil stratum is, the larger the excavation span is, the greater the boundary depth between the difficult stable region (DSR) and the easy stable region (ESR). Finally, combining with the characteristics of topographic and geomorphological and the statistical analysis of stratum thickness and its physical and mechanical parameters, the spatial distribution map of difficult and easy stable region of underground engineering along Qingdao metro is drawn. The research results provide theoretical basis and scientific basis for rational planning and design of urban underground space development and utilization.

1. Introduction

The urban underground space is generally in the geological body below the ground, and the geological conditions are the decisive factors that affect the difficulty and possibility of the value of underground space resources[1]. The development of urban underground space should take into account the geological factors such as urban topography, stratigraphic distribution and stratum thickness characteristics, and adapt to local conditions[2]. Stability is the primary concern in the development of underground space. The underground space development and construction process can only be carried out when the surrounding rock around the cavern is stable or temporarily stable. The surrounding rock dynamics of the cavern excavation are often associated with the surrounding rock classification[3-6].

The planning before the development of underground space is a hot topic of research. In the next few years, urban geology will be the research trend and hot spot of urban underground space[7]. At present, the research on the development and utilization of urban underground space based on the suitability of geological conditions is mainly based on the screening of index factors such as topography, geological structure, engineering geological hydrogeological conditions and adverse geological effects, through certain evaluation models and evaluation methods. Comprehensive classification of geological conditions for specific cities or regions[8~12]. From the geological point of view, there are few reports
on the study of the stability of urban underground space based on the full use of the surrounding rock stability. Based on giving full play to the self-stability of surrounding rock, this paper expounds the concept, ideas and research methods of urban underground space development and stable regional division; then the stability of urban underground space development under different overlying soft soil thickness and different excavation spans The regional division has been studied, and it is pointed out that the easy stable region (ESR) of the underground soft space in the upper soft stratum are all within the hard rock stratum. The thickness of the overlying rock above the cavern of the cavern is decisive for the difficult and stable area of the underground space, and the soft soil stratum. The larger the thickness, the larger the excavation span, the greater the boundary depth between the difficult stable region (DSR) and the easy stable region (ESR), and the greater the thickness of the corresponding boundary rock. Finally, combined with the Qingdao subway project example, the spatial distribution map of the stability of the underground space development along the Qingdao subway line is drawn.

2. Underground space development stability area division method

The fundamental goal of the design of excellent urban underground space development plan is to give full play to the self-stability of surrounding rock. Zoning research is an important and effective means of analyzing and evaluating underground engineering. From the perspective of giving full play to the self-stability of surrounding rock, this paper can determine whether the surrounding rock of cavern can meet the requirements of self-stability according to the underground space, and divide the urban underground space into two areas that are easy to stabilize and difficult to stabilize, and the underground space is easy to stabilize. After the excavation of the underground space, the surrounding rock does not need special treatment, but can maintain no harmful variation in a certain period of time, the engineering acceptable area; the difficult stable area is defined as self-stabilization from the surrounding rock. An area that is unacceptable in angle engineering.

SF based on numerical limit analysis is widely used in the analysis and evaluation of surrounding rock stability of underground engineering, and is used as the basis for design. When the safety factor (SF) of the numerical limit analysis method is 1.0, the surrounding rock of the underground space cavern is in an extremely stable state. Considering the complexity of surrounding rock and retaining a certain safety reserve, this paper takes SF 1.05 as the standard for the difficult and stable area of urban underground space, that is, the area with SF greater than 1.05 is easy to stabilize, and the area less than 1.05 is difficult to stabilize. region.

The upper soft lower hard stratum refers to a composite stratum composed of a loose soil stratum or a weak rock stratum in the upper part and a hard rock stratum in the lower part. Due to the significant differences in the mechanical characteristics of soft and hard strata, the problem of surrounding rock stability in the development of underground space in the upper soft and hard stratum has become a hot spot for scholars and engineers at home and abroad. Based on the values of the relevant parameters of the physical and mechanical properties of the rock and soil along the Qingdao Metro and the latest research results, the numerical calculation parameters of the overlying soft soil stratum and the underlying hard finite element are studied in the development area of the underground soft space of the upper soft and hard stratum (shown in Table 1).

| Stratigraphic type       | Severe (KN/m³) | Modulus of elasticity (Gpa) | Poisson ratio | Cohesion (Mpa) | Internal friction angle (°) |
|-------------------------|----------------|-----------------------------|---------------|----------------|---------------------------|
| Soft soil               | 22.5           | 0.05                        | 0.38          | 0.032          | 20                        |
| Hard rock stratum       | 24.5           | 5.0                         | 0.25          | 0.60           | 35                        |

Table 1: Mechanical parameters
For example, the single-arch straight wall underground cavern with a span of 20.8m is excavated at 6m in the soft and hard stratum below. For example, as shown in Figure 1, the method of finite element strength reduction safety factor is used to illustrate the regional division of underground space stability process. The numerical calculation of rock and soil is considered according to the ideal elastoplastic material, and the DP4 yield criterion is adopted, and the whole section is excavated at one time. The upper boundary of the calculation model is taken to the surface, and the lower boundary is taken above 65m (about 3.5 times excavation height) below the arch of the excavation section, and the distance between the left and right sides is 146m (about 7 times excavation span). During the calculation, the strength parameters c and φ are synchronously reduced, and the vertical displacement of the underground cavern is taken as the criterion of safety factor. The variation curve of the vertical displacement S of the cavern under different buried depth (DP) with the reduction factor k is shown in Fig. 2. The calculation results of the SF are shown in Table 2.

![Computational model](image1)
![S-k curve diagram](image2)

Fig.1 Computational model                  Fig.2 S-k curve diagram

**Table 2 Safety factor of 6 m soft stratum thickness**

| BD (m) | 2.0 | 4.0 | 6.5 | 7.0 | 12.0 | 15.0 | 18.0 | 30.0 | 86.0 | 106.0 | 150.0 |
|--------|-----|-----|-----|-----|------|------|------|------|------|-------|-------|
| SF     | 0.32| 0.35| 0.92| 1.22| 1.97 | 2.17 | 2.17 | 1.97 | 1.35 | 1.11  | 0.84  |

It can be seen that SF is 0.92 when the DP of the cavern is 6.5m, and SF is 1.22 when the DP is 7.0m. According to the boundary value of SF of 1.05, the intermediate interpolation method can be used to estimate the minimum boundary depth between the difficult and stable regions. It is 6.72m. With the increase of the buried depth, SF increases rapidly. When BD is 15.0m, SF reaches a maximum value of 2.17, and then BD is continuously increased, SF is continuously reduced. When BD is 106m, SF is 1.11, and when BD is 150m, SF is 0.84. When SF is 1.05 is 111.00m, that is, the maximum boundary depth between the difficult stable region and the easy stable region is 111.00m (As shown in Fig. 3).
3. Study on regional division of urban underground space stability under different weak strata and excavation span

3.1. Study on the influence of the thickness of soft soil stratum on the stability regional division

The influence of the regional division of the stability of the underground space in the upper soft and hard stratum is studied. The excavation sections are all single arch straight wall structures with a span of 20.8 m, as shown in Fig. 1. The soft soil stratum is at different excavation depths of 9 m, 12 m and 24 m. The calculation results of SF of the surrounding rock of the underground space cavern are shown in Tables 3~5.

Table 3: The SF of 9m soft stratum thickness

| BD(m) | 2.0 | 8.0 | 9.5 | 10.0 | 10.3 | 18.0 | 21.0 | 33.0 | 59.0 | 109.0 | 159.0 |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| SF    | 0.29| 0.35| 0.85| 1.01| 1.11| 1.79| 1.97| 1.79| 1.48| 1.11| 0.84 |

Table 4: The SF of 12m soft stratum thickness

| BD(m) | 2.0 | 10.0 | 13.0 | 13.6 | 13.9 | 21.0 | 24.0 | 36.0 | 112.0 | 132.0 |
|-------|-----|------|------|------|------|------|------|------|-------|-------|
| SF    | 0.29| 0.32 | 0.85 | 1.00 | 1.10 | 1.70 | 1.75 | 1.70 | 1.15 | 1.00 |

Table 5: The SF of 24m soft stratum thickness

| BD(m) | 5.0 | 25.0 | 26.5 | 27.0 | 27.5 | 36.0 | 44.0 | 54.0 | 124.0 | 144.0 |
|-------|-----|------|------|------|------|------|------|------|-------|-------|
| SF    | 0.24| 0.32 | 0.95 | 1.05 | 1.08 | 1.40 | 1.64 | 1.54 | 1.15 | 1.00 |

It can be seen that when the underground cavern is excavated under the condition of upper soft and hard stratum, SF of the surrounding rock of the cavern is less than 1.00 when the top of the cavern is in the upper soft soil stratum, and the surrounding rock cannot be self-stabilized and is in a difficult stable area. According to the criterion of the difficult to stabilize area and the easy stable area of the urban underground space with a safety factor of 1.05, the intermediate difference method is adopted. When the thickness of the soft soil stratum is 6m, 9m, 12m and 24m, the depth range corresponding to the easy stable area is 6.72~117.00m, 10.12~121.10m, 13.75~125.33m and 27.00~139.33m. According to the current urban underground space development shallow (0~10m), sub-shallow (10~30m), sub-deep (30~50m), depth (50~100m) four-level classification standard[22], the city sub-deep underground The space is in or partially in an easily stable area, and the sub-deep and deep underground spaces are in an easily stable area.

Further analysis found that the easy-to-stabilize areas are all within the rock stratum, and the thickness of the overburden above the cave vault is decisive for the difficult and stable areas of the underground space. When the thickness of the soft soil stratum is 6m, 9m, 12m and 24m, the thickness of the corresponding overburden is 0.72~111.00m, 1.12~112.10m, 1.75~113.33m and 3.00~115.33m, respectively, as shown in Table 6. The regional division of the stability of the underground soft upper hard stratum under different soft soil strata is shown in Fig. 5.

Table 6: ESR distribution of underground space

| Covering soil thickness (m) | Buried depth range (m) | Overburden thickness range (m) |
|----------------------------|-----------------------|-------------------------------|
| 6                          | 6.72~117.00           | 0.72~111.00                   |
| 9                          | 10.12~121.10          | 1.12~112.10                   |
| 12                         | 13.75~125.33          | 1.75~113.33                   |
| 24                         | 27.00~139.33          | 3.00~115.33                   |
3.2 Study on the influence of excavation span on the division of stability area

The influence of the excavation span of the upper soft and hard strata on the stability of urban underground space is 6.2m, 13.0m, 20.8m and 31.2m. As shown in Fig. 5, the thickness of the soft soil stratum is taken as 12.0 m. The calculation results of SFs of surrounding rock of underground space caverns under different buried depths are shown in Tables 7-9.

Table 7: The SF of 6.2 m excavation span

| BD (m) | 2.0   | 10.0  | 12.1  | 12.5  | 15.0  | 21.0  | 36.0  | 112.0 | 162.0 |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| SF     | 0.69  | 0.63  | 0.92  | 1.48  | 2.88  | 3.49  | 2.88  | 1.22  | 0.92  |

Table 8: The SF of 13.0 m excavation span

| BD (m) | 2.0   | 10.0  | 12.5  | 13.0  | 18.0  | 24.0  | 62.0  | 112.0 | 162.0 |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| SF     | 0.43  | 0.43  | 0.92  | 1.11  | 2.17  | 2.62  | 1.91  | 1.22  | 0.92  |

Table 9: The SF of 31.2 m excavation span

| BD (m) | 13.0  | 14.0  | 15.0  | 22.0  | 32.0  | 62.0  | 92.0  | 112.0 |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|
| SF     | 0.82  | 1.03  | 1.15  | 1.45  | 1.52  | 1.25  | 1.10  | 1.00  |

According to the safety standard of 1.05, the urban underground space is difficult to stabilize and the area is easy to stabilize. The difference analysis method is adopted. When the excavation span is 6.2m, 13.0m, 20.8m and 31.2m, BD range corresponding to the easy stable area.The order is 12.19~140.33m, 12.84~140.33m, 13.75~125.33m and 14.17~102.00m. The sub-deep underground space of the city is in a difficult stable area, and the sub-deep and deep underground spaces are in an easy stable area. When the excavation span is 6.2m, 13.0m, 20.8m and 31.2m, the thickness of the overburden corresponding to the easy-to-stabilize area of the underground space is 0.19~128.33m, 0.84~128.33m, 1.75~113.33m, and 2.17~90.00m, as shown in Table 10.

Table 10: ESR division of underground space in different excavation

| Excavation span | Buried depth range (m) | Overburden thickness range (m) |
|-----------------|------------------------|-------------------------------|
| 6.2m            | 12.19~140.33           | 0.19~128.33                   |
| 13.0m           | 12.84~140.33           | 0.84~128.33                   |
| 20.8m           | 13.75~125.33           | 1.75~113.33                   |
| 31.2m           | 14.17~102.00           | 2.17~90.00                    |
3.3 Discussion on regional division of urban underground space stability

At present, the development of underground space in large and medium-sized cities in China is mainly concentrated in the sub-shallow space \(^{[23]}\) dominated by rail transit. For cities with shallow depths such as Qingdao, Dalian, Xiamen, etc., the sub-shallow underground space is within the sensitive range of difficult to stabilize areas and easy to stabilize areas. The easy-to-stabilize areas of the upper soft and hard ground are all within the rock stratum. The thickness of the overburden above the cave vault is decisive for the difficult area of the underground space and the easy stable area. The greater the thickness of the overlying soft soil stratum, the larger the excavation span, the greater the boundary depth between the difficult and stable regions, and the greater the thickness of the corresponding boundary overburden. When excavating a 20.8m single arch straight wall underground cavern, when the thickness of the overlying soft soil stratum is 6m, 9m, 12m and 24m, the boundary depth of the difficult zone is 6.72m, 10.12m, 13.75m, 27.00m. The thickness of the corresponding boundary overburden is 0.72m, 1.12m, 1.75m, 3.00m, the thickness of the soft soil stratum is 12m, and the underground cavern with excavation spans 6.2m, 13.0m, 20.8m, 31.2m is difficult to stabilize and easy. The depth of the boundary of the stable region is 12.19m, 12.84m, 13.75m, 14.17, and the thickness of the corresponding boundary overburden is 0.19m, 0.84m, 1.75m, 2.17m.

4. Engineering case analysis

The total length of the Qingdao Metro Line 3 is 24.78km, and there are 22 stations, all of which are underground lines, which are mainly excavated by drilling and blasting. The terrain along the subway line is undulating as a whole, with a maximum relative height difference of about 45m. The stratigraphic distribution is mainly distributed from the top to the bottom, the Quaternary loose accumulation stratum, the strongly weathered, moderately weathered, micro (un) weathered granite rock stratum, with significant upper soft and hard stratum distribution characteristics. The structural structure of the strongly weathered rock strata is partially destroyed. The core is rock-soil or semi-soil and semi-soil. The core pendulum in the standard penetration test is gravel-like. The rock hardness is extremely soft rock, and the rock mass is extremely broken. The basic quality grade of the rock mass is V. The structure of the middle weathered rock stratum is relatively complete, and the core is mostly fragmented-blocklike. The hardness of the rock is soft to hard rock, and the basic quality grade of the rock mass is III–IV. The structure of the micro-weathered rock stratum is complete, and the core is mostly massive ~ monolithic, which is a hard-hard rock, generally belonging to the II–III-level surrounding rock.

According to the statistical analysis of 1449 geological borehole samples along the subway, the average thickness of the Quaternary stratum is 5.76m, the average thickness of the strong weathering stratum is 6.47m, and the average thickness of the middle weathering stratum is 4.48m. The Quaternary strata and the strongly weathered stratum are classified into soft soil strata. The strata below the middle weathering are called hard rock strata. The average thickness of the soft soil along the Qingdao Metro is 10.94m, which is 57% within 12m and 75% within 15m. 88% within 18m, as shown in Table 11.

Table 11 The soft stratum thickness distribution
According to the statistical analysis results of stratum thickness along the metro, combined with the topography and geomorphology, the linear interpolation calculation of the boundary depth of the underground space stability of each two adjacent stations is carried out by using Matlab as the benchmark with a single arch large span tunnel with a span of 20.8 m. Obtain the distribution of the underground space stable area of several mileage points between each two adjacent stations. Furthermore, the distribution of the stable area of each mileage point is plotted on the longitudinal section of the whole line, and the spatial distribution map of the stable area of the underground space development along the subway line is obtained, as shown in Fig. 7.

![ESR spatial distribution map of underground space along Qingdao metro](image)

**Fig. 7** ESR spatial distribution map of underground space along Qingdao metro

### 5. Summary

1. From the perspective of giving full play to the self-stability of surrounding rock, the basic concepts, research ideas and research methods of the stable regional division of underground space development in the upper soft and hard stratum are expounded.

2. The easy stable region (ESR) of the underground soft space of the upper soft stratum are all within the rock stratum. The thickness of the overlying rock above the vault of the cavern is decisive for the difficult area of the underground space and the easy stable area. The greater the thickness of the soft soil stratum, the larger the excavation span, the greater the boundary depth between the DSR and the ESR.

3. According to the statistical analysis results of the thickness of the stratum along the metro line, combined with the topography and geomorphology, the spatial distribution map of the stable area of the underground space development along the Qingdao metro line is drawn.

### References

[1] Jiang Xu, Wang Tingting, Mu Jing Research on the application of suitability and resources in underground space development[J]. Chinese Journal of Underground and Space and Engineering, 2018,14(5):1145-1153.

[2] Hu Xuexiang, Liu Ganbin, Tao Haibing. Research on Evaluation suitability for the development of underground space in Ningbo City based on Arc GIS [J]. Chinese Journal of Underground and Space and Engineering, 2016,12(6):1439-1444.

[3] Guang Baoshu. Key techniques of the tunnel by mining method [M]. Binjing: China Communications Press, 2016.

[4] (Standard for engineering classification of rock mass(GB/T50218-2014)[S].Beijing:China Planning Press , 2014.

[5] Code for design of railway tunnel(TB 10003-2016/J449-2016)[S].Beijing: Chinese Railway Press, 2017.

[6] Technical code for engineering of ground anchorages and shotcrete support (GB50086-2015) [S]. Beijing: Chinese Planning Press, 2015.)

[7] Zhang Mengxia, Zheng Xinqi, Wang Kaijian. Analysis on the knowledge of foreign Research on urban underground space[J]. Science of Surveying and Mapping, 2018,43(7):180-186.

[8] Liu Kun, Peng Jian, Peng Fangle. Evaluation model For the suitability of underground space resources exploitation and utilization[J]. Chinese Journal of Underground and Space and Engineering, 2011,7(2):220-231. (in Chinese)
[9] Wu Binghua, Zhang Shuijun, Xu Penglei et al. Environment suitability assessment of underground space development in Ningbo city[J]. Chinese Journal of Underground and Space and Engineering, 2017, 13(8): 16-21.

[10] Shi Wei, Wang Youlin. Evaluation and analysis of geological environment suitability for the development of underground space in Weinan[J]. Ground Water, 2018, 40(4): 134-137.

[11] Liu Yunlai, Wu Jianguang, Peng Peiyu, et al. Suitability evaluation for the utilization of underground space in consideration of geo-environmental factors[J]. Journal of Yangtze River Scientific Research Institute, 2017, 34(5): 58-67.

[12] Zhang Jinjin, Ma Chuannong, Kuang Heng, etc. Geo-environment suitability assessment with variable weight for underground space exploitation in Zhengzhou[J]. Hydrogeology and Engineering Geology, 2016, 43(2): 118-125.

[13] Hoek E and Brown E.T. Underground excavations in Rock [M], The Institute of Mining and Metallurgy, 1980.

[14] Guan Baoshu. Tunneling by mining method: lecture I: surrounding rock [J]. Tunnel Construction, 2015, 10(35): 982-988. (in Chinese)

[15] Zheng Yingren. Development and Application of Numerical Limit Analysis for Geological Materials [J]. Chinese Journal of Rock Mechanics and Engineering, 2012, 31(7): 1297-1316.

[16] Zhang Ziguang, Qiu Wenge. Research on the stability region division of urban underground space of Qingdao city[J]. Chinese Journal of Underground and Space and Engineering, 2018, 14(4): 881-892.

[17] Zhang Ziguang. Study on the reasonable buried depth of metro tunnel in the two element strata of soil and rock [M]. Chengdu: Southwest Jiaotong University, 2017.12

[18] Zhang Ziguang, Qiu Wenge. Discussion and Case study of the rational ratio of rock mass thickness and tunnel span of mined subway tunnels in upper-soft and lower-hard ground[J]. Modern Tunnelling Technology, 2015, 52(6): 28-35.

[19] Wang Xudong, Zhou Shenghua, Chi Jianping, Wu Xuefeng. Study on Shallow-Buried Tunnel's Thickness-Span Ratio in Upper-Soft Lower-Hard Ground [J]. Chinese Journal of Underground and Space and Engineering, 2011, 7(4): 700-705

[20] Cong Yu, Guo Hui, Zheng Yingren, Feng, Cong Yu, Guo Hui, Zheng Yingren, Feng, Cong Yu, Guo Ying, Feng Xiating, et al. Xiating et al. On the rock classification method for metro engineering[J]. Modern Tunnelling Technology, 2016, 53(3): 33-41.

[21] Yang Zhen, Zheng Yingren, Zhang Hong, et al. Exploring computational method of designing the supporting structure of rock tunnel[J]. Rock and Soil Mechanics, 2009, 30(s): 148-153.

[22] Shao Jizhong. Research on the Spatial Morphology Development of Urban Underground Space[J]. Urban Insight, 2015, 5: 156-165.

[23] Zhu Hehua, Luo Xiao, Peng Fangle, et al. Urban underground space planning in China[J]. China Engineering Sciences, 2017, 19(6): 12-17.